

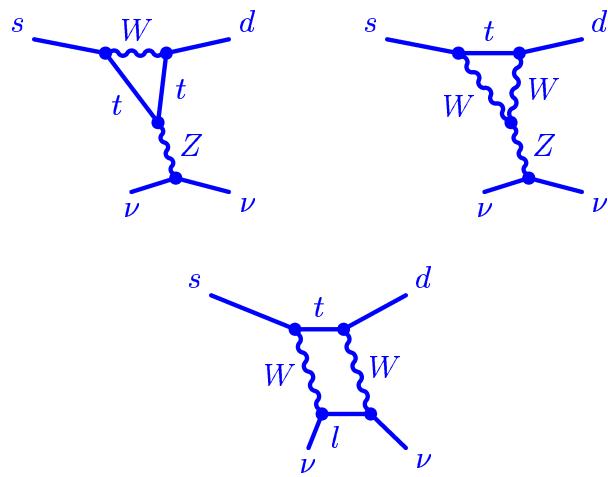
## Results and Prospects for $K \rightarrow \pi \nu \bar{\nu}$

David E. Jaffe, BNL

- Introduction
- $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ : E949 experimental method and results
- $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ : KOPIO experimental method and prospects
- Summary and outlook



# $K \rightarrow \pi \nu \bar{\nu}$ in the Standard Model and beyond



- Negligible long distance effects ( $10^{-13}$ )
- Hadronic matrix element via isospin analog  $K^+ \rightarrow \pi^0 e^+ \nu$

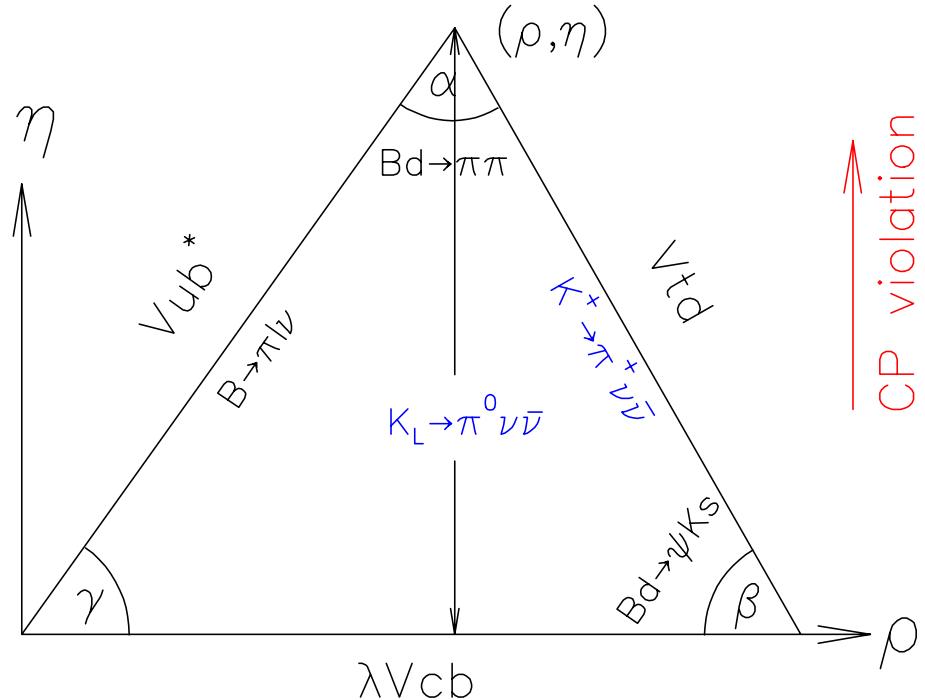
	$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu})$
top dep.	$ V_{ts}^* V_{td} $	$Im(V_{ts}^* V_{td})$
Msmt <sup>a,b,c</sup>	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$	$< 5.9 \times 10^{-7}$ $< 4.4 \times \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
SM <sup>d</sup>	$(0.77 \pm 0.11) \times 10^{-10}$	$(0.26 \pm 0.05) \times 10^{-10}$
SM Uncert. <sup>f</sup>	7%	2%
MFV <sup>g</sup>	$1.91 \times 10^{-10}$	$0.99 \times 10^{-10}$
EZP <sup>h</sup>	$(0.75 \pm 0.21) \times 10^{-10}$	$(3.1 \pm 1.0) \times 10^{-10}$

Limits are at 90% CL.

## References

- |     |  |     |                             |
|-----|--|-----|-----------------------------|
| (a) | PRL <b>88</b> (2002) 041803                                  | (b) | PR <b>D61</b> (2000) 072006 |
| (c) | PL <b>B398</b> (1997) 163                                    | (d) | hep-ph/0307014              |
| (e) | hep-ph/0212321   | (f) | hep-ph/0101336              |
| (g) | Minimal Flavor Violation, Buras, hep-ph/0310208              |     |                             |
| (h) | Enhanced $Z^0$ Penguins, Buras <i>et al.</i> , hep-ph/040211 |     |                             |

## “Golden” modes and the CKM unitarity triangle



Process	Expts
$\mathcal{B}(K_L^0 \rightarrow \pi^0 \bar{\nu})$	KOPIO, E391a
$\mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu})$	E787/E949
$\mathcal{A}(B \rightarrow J/\psi K_S^0; t)$	BaBar, Belle
$\Delta m_s / \Delta m_d$	CDF, D0

Comparison of  $|V_{td}|$  from  $\mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu})$  and  $\Delta m_s / \Delta m_d$  is an important test of the SM.

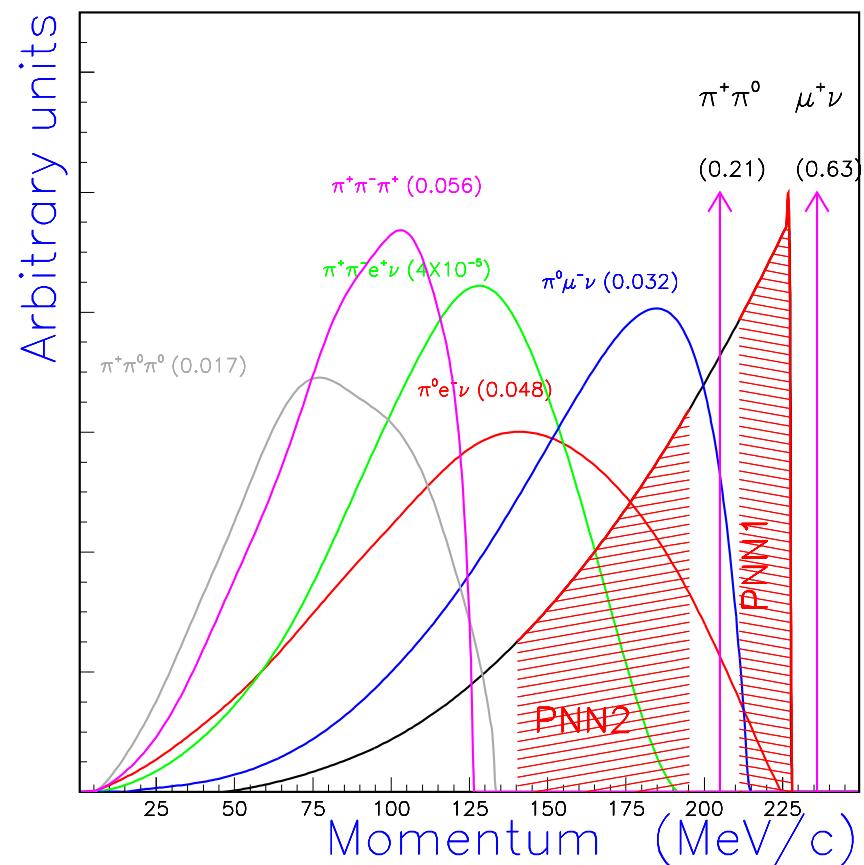
Comparison of  $\sin 2\beta$  from  $\mathcal{B}(K_L^0 \rightarrow \pi^0 \bar{\nu}) / \mathcal{B}(K^+ \rightarrow \pi^+ \bar{\nu})$  and  $\mathcal{A}(B \rightarrow J/\psi K_S^0; t)$  is perhaps the definitive test CP violation in the SM.

Name	“PNN2”	“PNN1”
$P_\pi$ (MeV/c)	[140,195]	[211,229]
Years	1996- 97	1995-98
Stopped $K^+$	$1.7 \times 10^{12}$	$5.9 \times 10^{12}$
Candidates	1	2
Background	$1.22 \pm 0.24$	$0.15 \pm 0.05$
$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$	$< 22 \times 10^{-10}$	$(1.57^{+1.75}_{-0.82}) \times 10^{-10}$

**E787**  
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$   
**results**

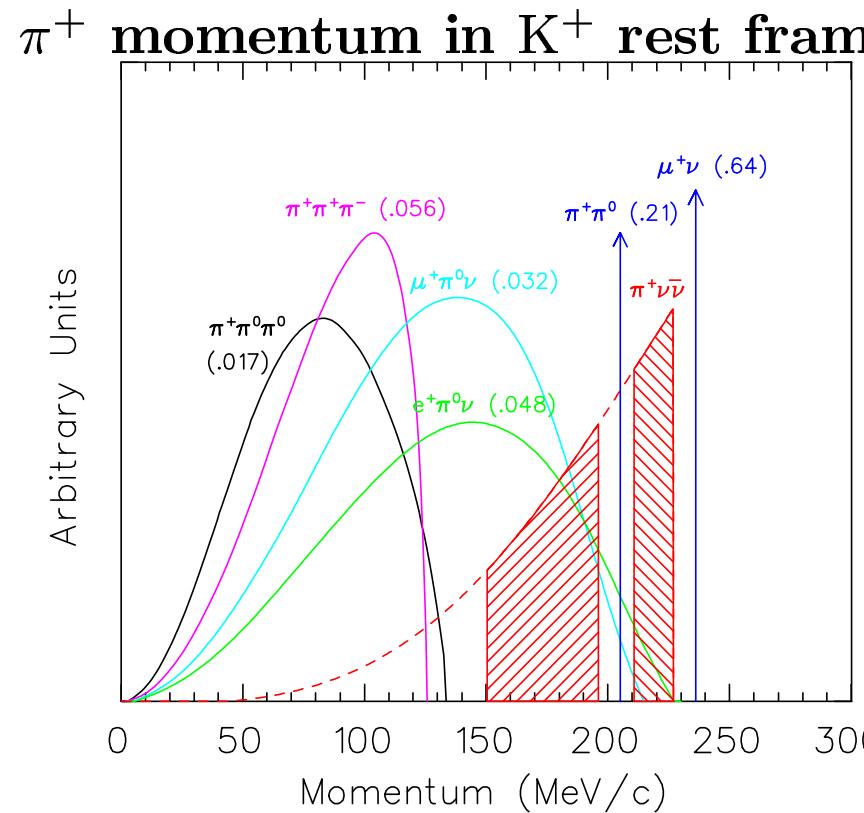
**PNN1:** PRL 88, 041803 (2002).

**PNN2:** Limit at 90%CL is combined result from 1996 (PL B537, 211 (2002)) and 1997 (hep-ex/0403034) data.



# $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and background rates

Process	Rate
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	$0.77 \times 10^{-10}$
$K^+ \rightarrow \pi^+ \pi^0$	$2113000000.00 \times 10^{-10}$
$K^+ \rightarrow \mu^+ \nu$	$6343000000.00 \times 10^{-10}$
$K^+ \rightarrow \mu^+ \nu \gamma$	$55000000.00 \times 10^{-10}$
$K^+ \rightarrow \pi^0 \mu^+ \nu$	$327000000.00 \times 10^{-10}$
CEX	$\sim 46000.00 \times 10^{-10}$
Scattered $\pi^+$ beam	$\sim 25000000.00 \times 10^{-10}$



$\text{CEX} \equiv (K^+ n \rightarrow K^0 X) \times (K^0 \rightarrow K_L^0) \times (K_L^0 \rightarrow \pi^+ \ell^- \nu)$   
 $\ell^-$  is  $\mu^-$  or  $e^-$   
 $K^+ n \rightarrow K^0 X$  rate is empirically determined.

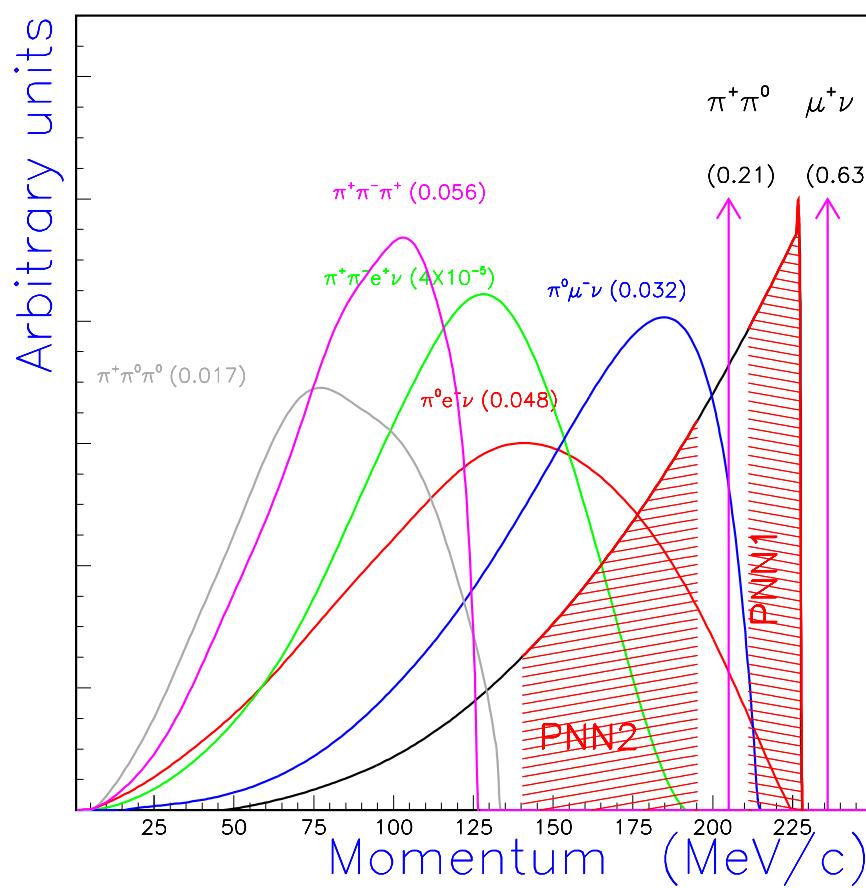
# E787 experimental method

**Measure everything possible.**

- Independent measurements of range(R), energy(E) and momentum(P) of  $\pi^+$
- Positive identification of incoming  $K^+$  and outgoing  $\pi^+$
- Veto extra photons and charged particles

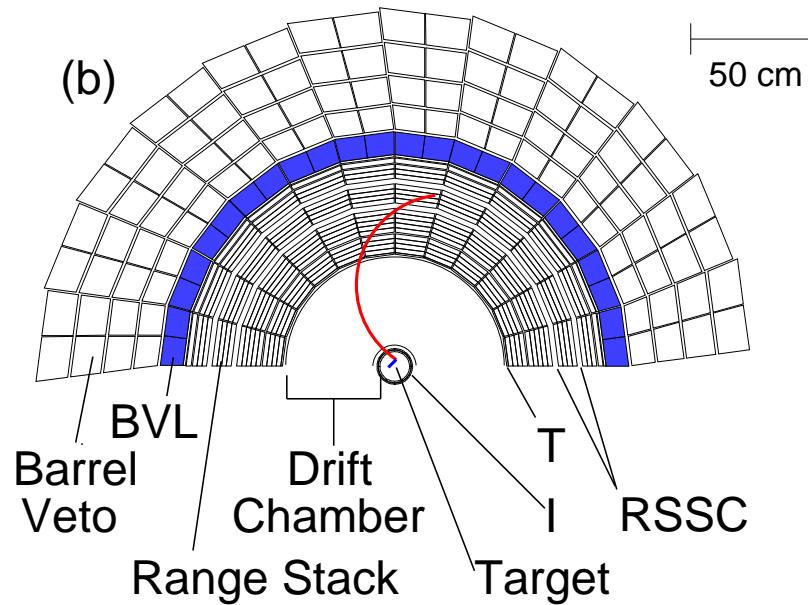
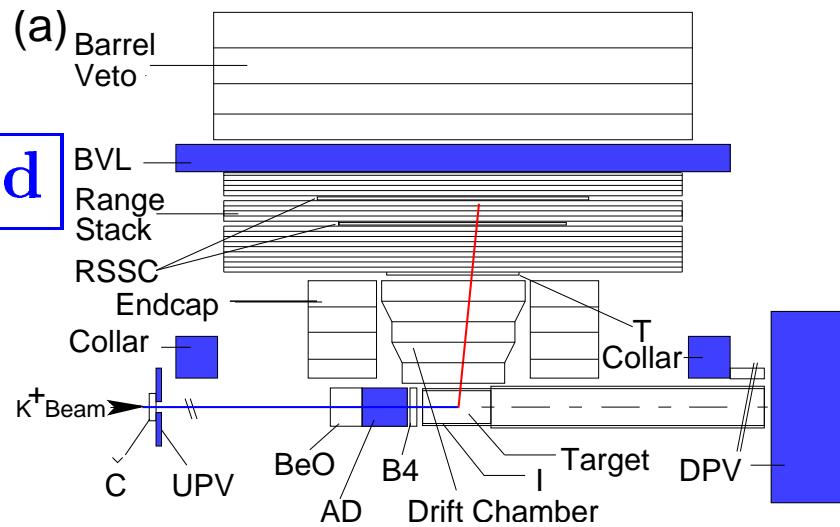
Background must be suppressed by  $10^{11}$ :  $Bkgd/S(SM) < 0.1$

Measure background with data — set cuts based on 1/3 of data and evaluate bkgd with remaining 2/3.



## E949 experimental method

- $\sim 700 \text{ MeV}/c K^+$  beam
- Stop  $K^+$  in scint. fiber target
- Wait at least 2 ns for  $K^+$  decay
- Measure  $P$  in drift chamber
- Measure range  $R$  and energy  $E$  in target and range stack (RS)
- Stop  $\pi^+$  in range stack
- Observe  $\pi^+ \rightarrow \mu^+ \rightarrow e^+$  in RS
- Veto photons, charged tracks
- **New/upgraded detector elements**



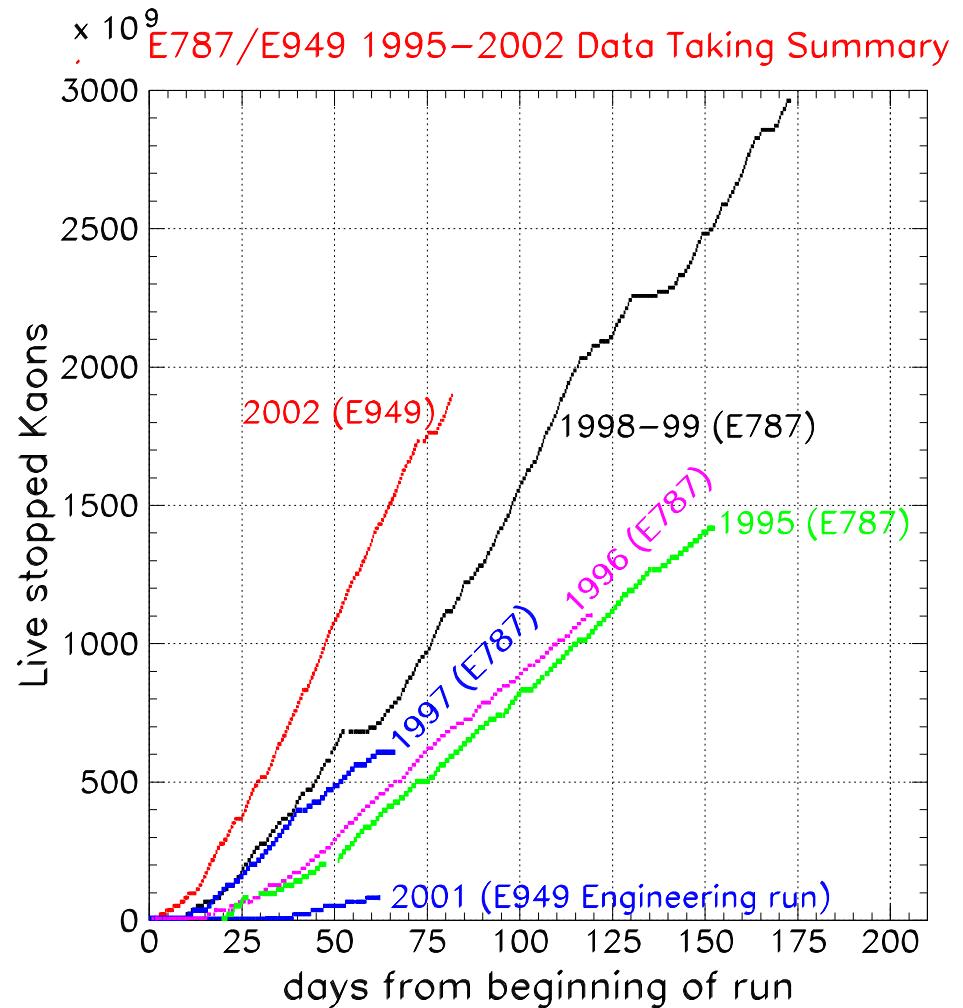
## E949 status for 2002 data taking

### Upgrades to E787:

- More protons/sec from AGS
- Improved photon veto hermeticity
- Improved tracking and energy resolution
- Higher rate capability due to DAQ and trigger improvements

### Not optimal in 2002:

1. Spill duty factor.
2. Proton beam momentum.
3. K/ $\pi$  electrostatic separators.

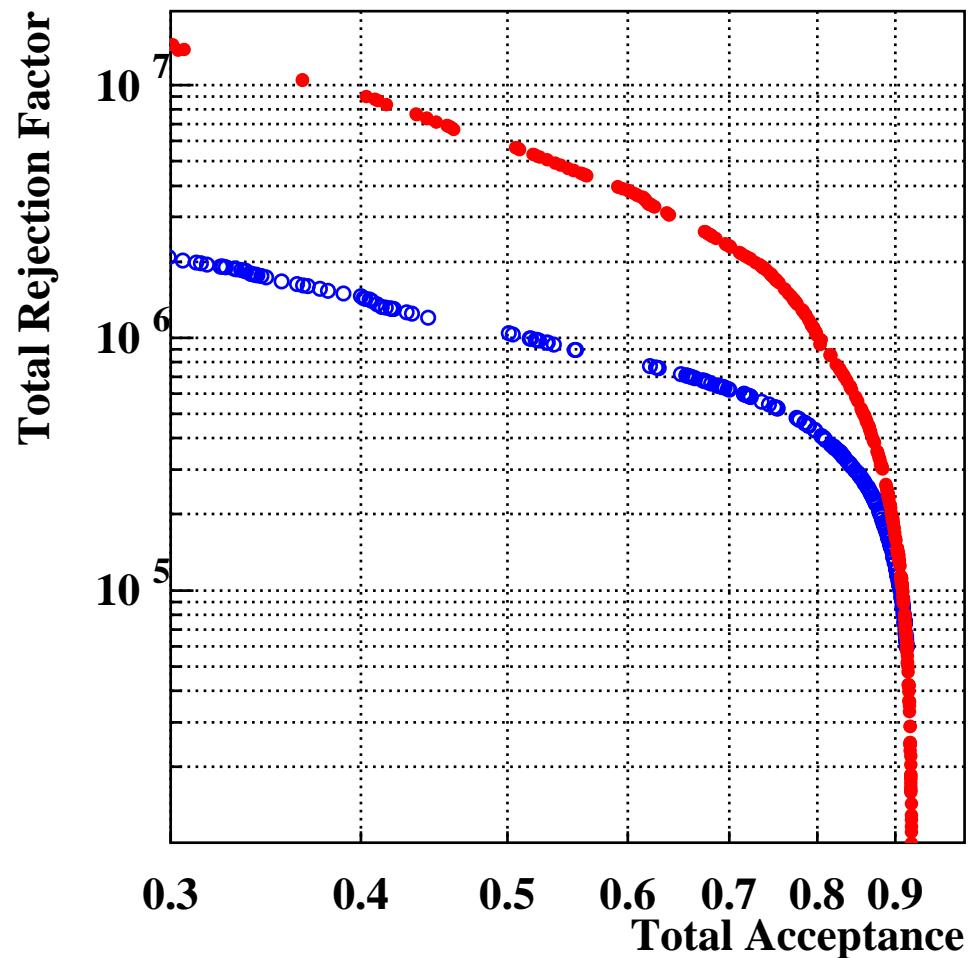


## E949: Upgrade of photon veto

Improved photon veto hermeticity.

Figure: background **Rejection** as a function of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  signal **Acceptance** for the photon veto cut for [E787](#) and [E949](#).

$\sim 2\times$  better rejection at nominal **PNN1** acceptance of 80% or  
 $\sim 5\%$  more acceptance in E949 with same rejection as E787.



## E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . Verify by measuring  $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0)$ .
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.

## Background suppression

Source	Suppression method			
	Kinematics	Particle ID	Veto	Timing
$K^+ \rightarrow \mu^+ \nu(\gamma)$	✓	✓	(✓)	
$K^+ \rightarrow \pi^+ \pi^0$	✓		✓	
Scattered beam		✓		✓
CEX			✓	✓

$$\text{CEX} \equiv K^+ n \rightarrow K^0 p , K_L^0 \rightarrow \pi^+ \ell^- \nu$$

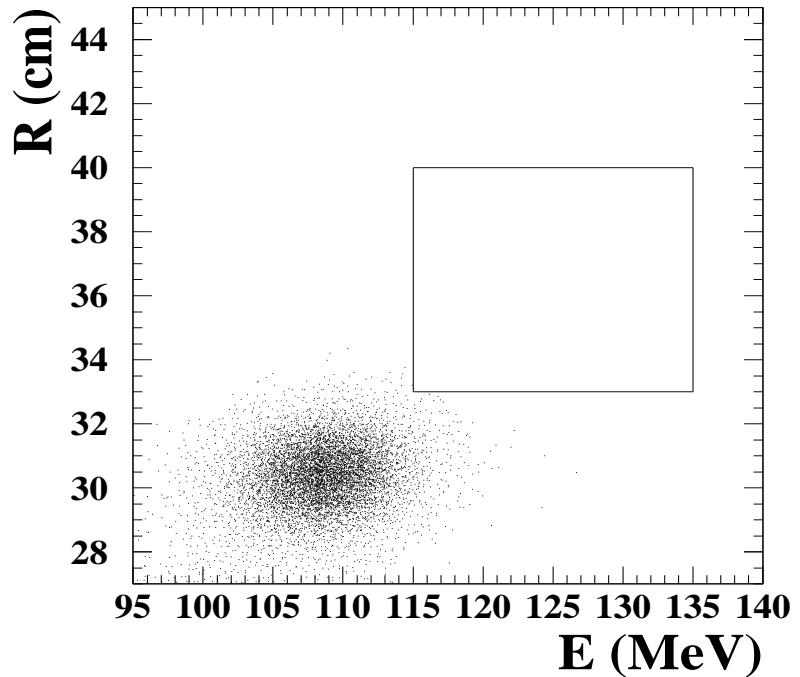
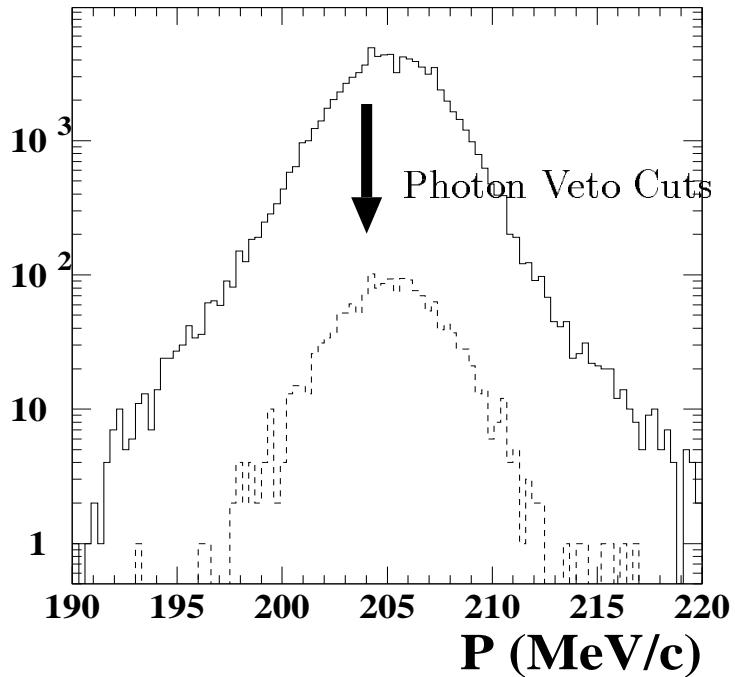
Particle ID includes beam Cherenkov,  $dE/dx$  and  $\pi \rightarrow \mu \rightarrow e$  detection

Veto includes both photon and charged particle vetoing

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## Example: $K^+ \rightarrow \pi^+\pi^0$ background rejection



**Left:** Kinematically selected  $K^+ \rightarrow \pi^+\pi^0$  with photon veto applied.

Photon veto: Typically 2-5 ns time windows and 0.2 - 3 MeV energy thresholds

**Right:** Select photons. Phase space cuts in  $P$ ,  $R$ ,  $E$ .

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## Verify background by loosening cuts

Define rejection power  $\equiv 1$  when cuts are set to produce pre-determined signal region (“signal box”)

Relax cut to reduce rejection by  $\times 10$ . New, larger region should have  $10 \times$  background of signal box.

Example: For  $K^+ \rightarrow \pi^+\pi^0$  background, simultaneously loosen photon veto (PV) and kinematic (KIN) cuts each by  $\times 10$ . Expect  $10 \times 10 = 100$  times more background than that of the signal box.

## Compare background prediction with observation near signal region

	PV×KIN	$10 \times 10$	$20 \times 20$	$20 \times 50$	$50 \times 50$	$50 \times 100$
$K_{\pi 2}$	Observed	3	4	9	22	53
	Predicted	1.1	4.9	12.4	31.1	62.4
$K_{\mu 2}$	TD×KIN	$10 \times 10$	$20 \times 20$	$50 \times 50$	$80 \times 50$	$120 \times 50$
	Observed	0	1	12	16	25
$K_{\mu m}$	Predicted	0.35	1.4	9.1	14.5	21.8
	TD×KIN	$10 \times 10$	$20 \times 20$	$50 \times 20$	$80 \times 20$	$80 \times 40$
$K_{\mu m}$	Observed	1	1	4	5	11
	Predicted	0.31	1.3	3.2	5.2	10.4

$K_{\pi 2} \equiv K^+ \rightarrow \pi^+ \pi^0$ ;  $K_{\mu 2} \equiv K^+ \rightarrow \mu^+ \nu$ ;

$K_{\mu m} \equiv K^+ \rightarrow \mu^+ \nu \gamma$ ,  $K^+ \rightarrow \pi^0 \mu^+ \nu$  and  $K^+ \rightarrow \pi^+ \pi^0$  with  $\pi^+ \rightarrow \mu^+ \nu$  decay in flight

TD $\equiv \pi \rightarrow \mu \rightarrow e$  identification, PV $\equiv$ Photon Veto rej., KIN $\equiv$  kinematic rej.  
 $M \times N \equiv$  reduction in rejection with respect to signal region

## Compare background prediction with observation near signal region

Quantify consistency: Fit  $N_{\text{obs}} = cN_{\text{pred}}$  and expect  $c = 1$ .

Background	$c$	$\chi^2$	Probability	Total background
$K_{\pi 2}$	$0.85^{+0.12}_{-0.11}$	0.17		$0.216 \pm 0.023$
$K_{\mu 2}$	$1.15^{+0.25}_{-0.21}$	0.67		$0.044 \pm 0.005$
$K_{\mu m}$	$1.06^{+0.35}_{-0.29}$	0.40		$0.024 \pm 0.010$

Deviation of  $c$  from unity is taken into account in evaluation of  
 $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

Beam and CEX background is  $0.014 \pm 0.003$

The calculated number of background events in the signal region is  
 $0.30 \pm 0.03$  from all background sources.

## E787 and E949 analysis strategy

- A priori identification of background sources.
- Suppress each background source with at least two independent cuts.
- Backgrounds cannot be reliably simulated: measure with data by inverting cuts and measuring rejection taking any (small) correlations into account.
- To avoid bias, set cuts using 1/3 of data, then measure backgrounds with remaining 2/3 sample.
- Verify background estimates by loosening cuts and comparing observed and predicted rates.
- Use MC to measure geometrical acceptance for  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ . Verify by measuring  $\mathcal{B}(K^+ \rightarrow \pi^+ \pi^0) = 0.215 \pm 0.005$ .  
World average value is  $0.2113 \pm 0.0014$ .
- “Blind” analysis. Don’t examine signal region until all backgrounds verified.

## E949 improved analysis strategy<sup>†</sup>

1. E787 background estimation methods are reliable
2. Divide signal region into cells and calculate background ( $b_i$ ) and signal acceptance ( $s_i$ ) for each cell. Example: Tighten PV cut to select subregion with 1/10 of the total predicted  $K^+ \rightarrow \pi^+\pi^0$  background within “signal box”
3. Can calculate  $\mathcal{B}(K^+ \rightarrow \pi^+\nu\bar{\nu})$  using  $s_i/b_i$  of any cells containing candidates using likelihood ratio method.
4. Increase total size of signal region to increase acceptance at cost of more total background

<sup>†</sup> With age comes wisdom.

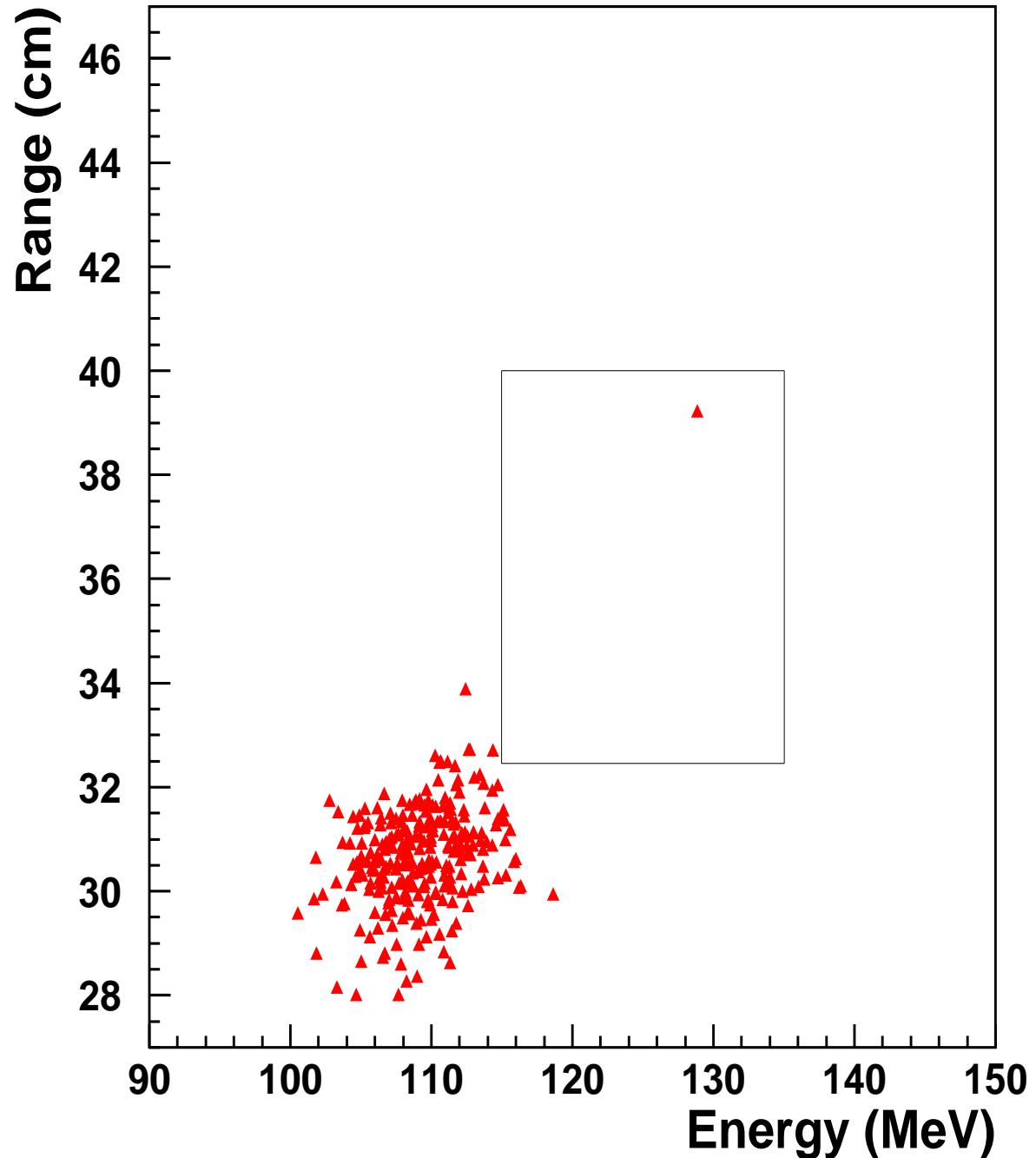
## Opening the box

Range (cm) *vs* Energy (MeV) for E949 data after all other cuts applied.

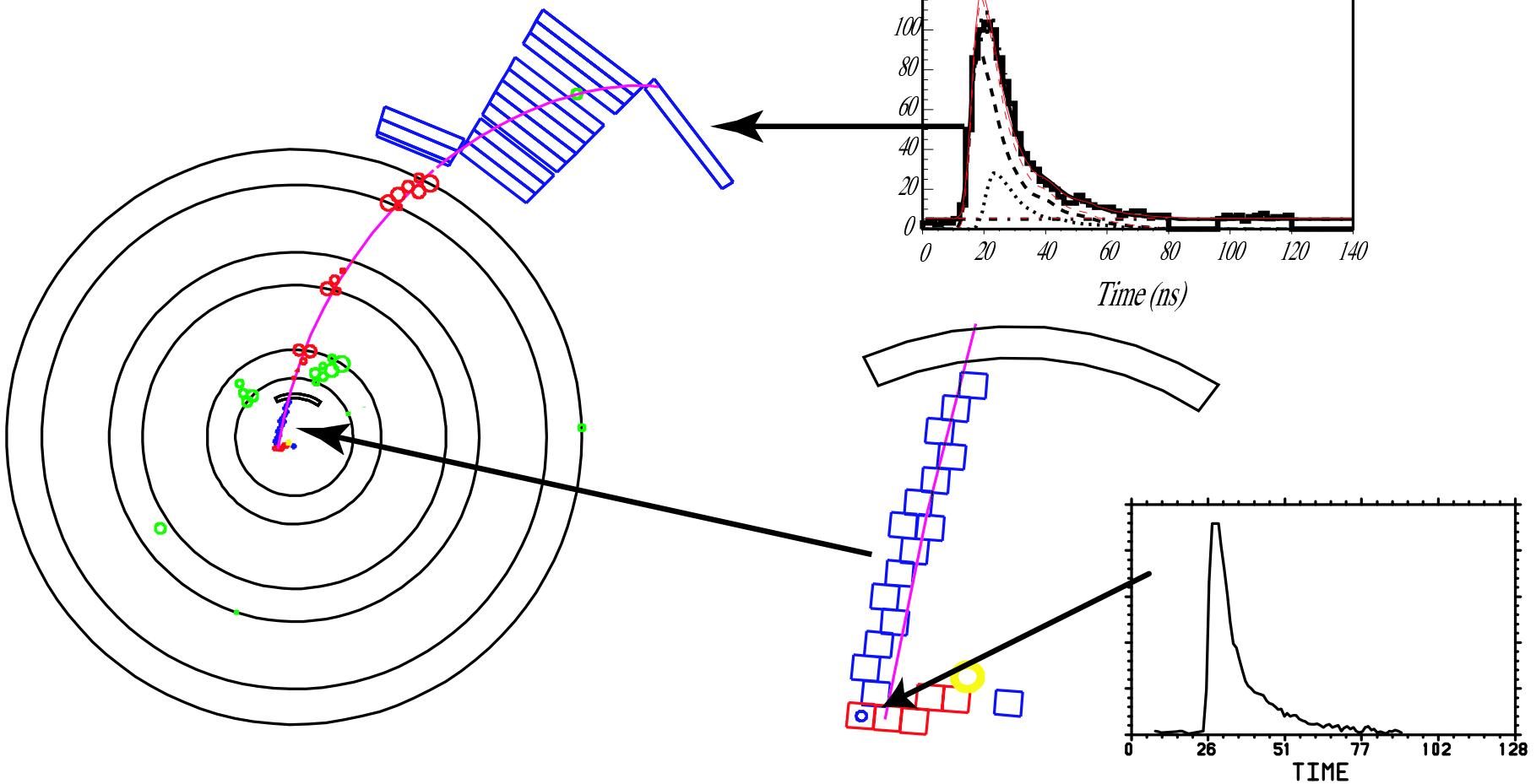
Solid line shows signal region.

**Single candidate found.**

Cluster near 110 MeV is unvetoed  $K^+ \rightarrow \pi^+\pi^0$ .



## Event display



**How likely is it that the candidate is due to known background?**

**Question:** Suppose we do 100 experiments, how many will have a candidate from a known background source that is as signal-like or more signal-like than the observed candidate?

**Answer:**  $\sim 7$

The sum of background in all cells with  $s_i/b_i$  greater or equal to the cell containing the observed candidate is 0.077. The probability that 0.077 could produce one or more events is 0.074 ( $\sim 7/100$ ).

The E949 candidate is more likely to be due to background than the two E787 candidates.

Candidate	E787A	E787C	E949A
Probability	0.006	0.02	0.07

	E787	E949	
Stopped K <sup>+</sup> ( $N_K$ )	$5.9 \times 10^{12}$	$1.8 \times 10^{12}$	
Total Acceptance	$0.0020 \pm 0.0002$	$0.0022 \pm 0.0002$	
Total Background	$0.14 \pm 0.05$	$0.30 \pm 0.03$	
Candidate	E787A	E787C	E949A
$S_i/b_i$	50	7	0.9
$W_i$	0.98	0.88	0.48

$b_i$  = background of cell containing candidate

$S_i \equiv \mathcal{B} A_i N_K$  = signal for cell containing candidate

$A_i$  = acceptance

$\mathcal{B}$  = measured central value of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  branching fraction

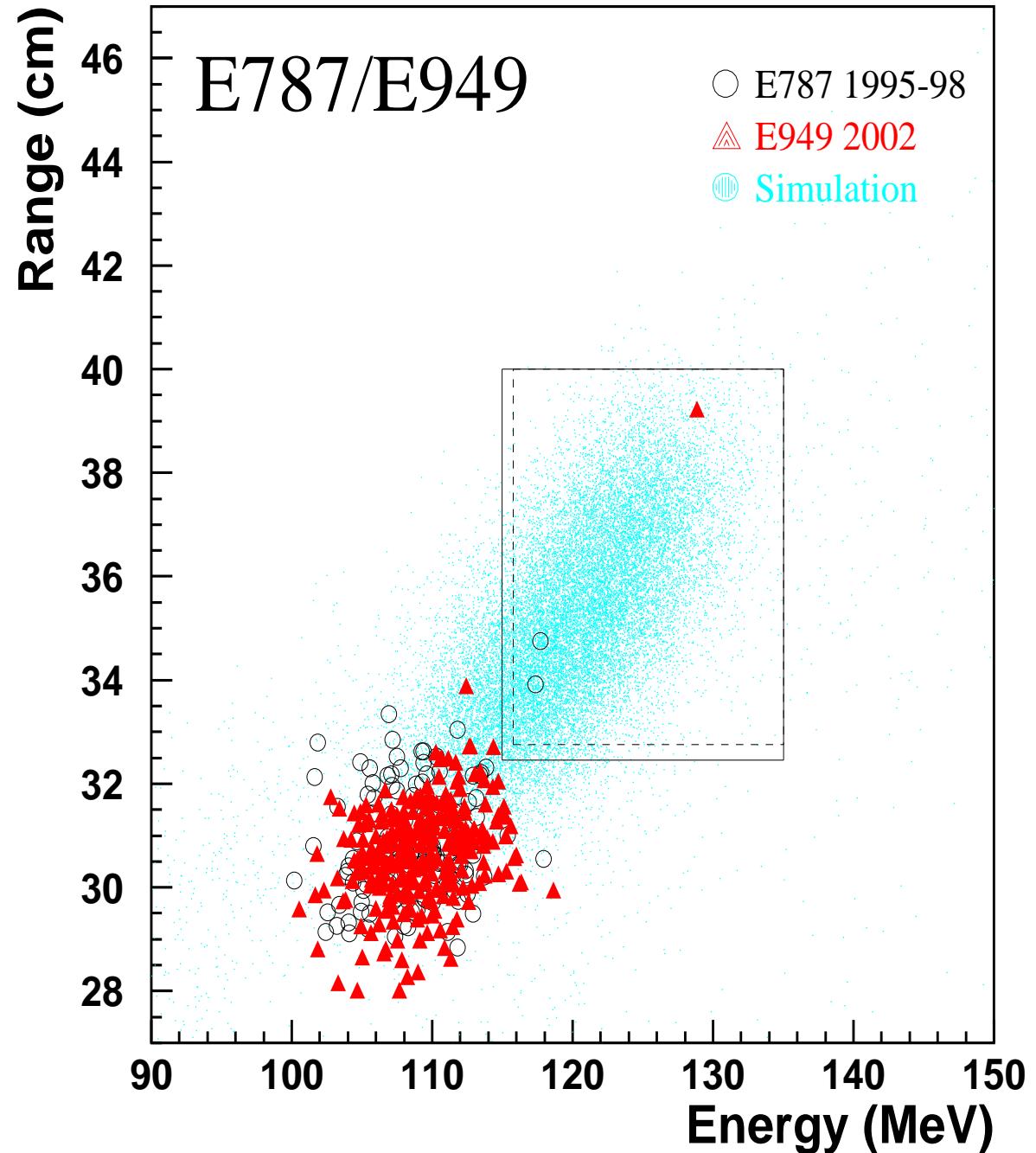
$W_i \equiv S_i/(S_i + b_i)$  = event weight

Event weight  $W_i$  and  $S_i/b_i$  assumes SM signal hypothesis as well as calculated background.

Range (cm) *vs* Energy (MeV) for combined E787 and E949 data after all other cuts applied.

Dashed line is E787 signal region.

Solid line is E949 signal region.



## Combined E787 and E949 results for $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10} \quad (68\% \text{CL interval})$$

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) > 0.42 \times 10^{-10} \text{ at } 90\% \text{CL.}$$

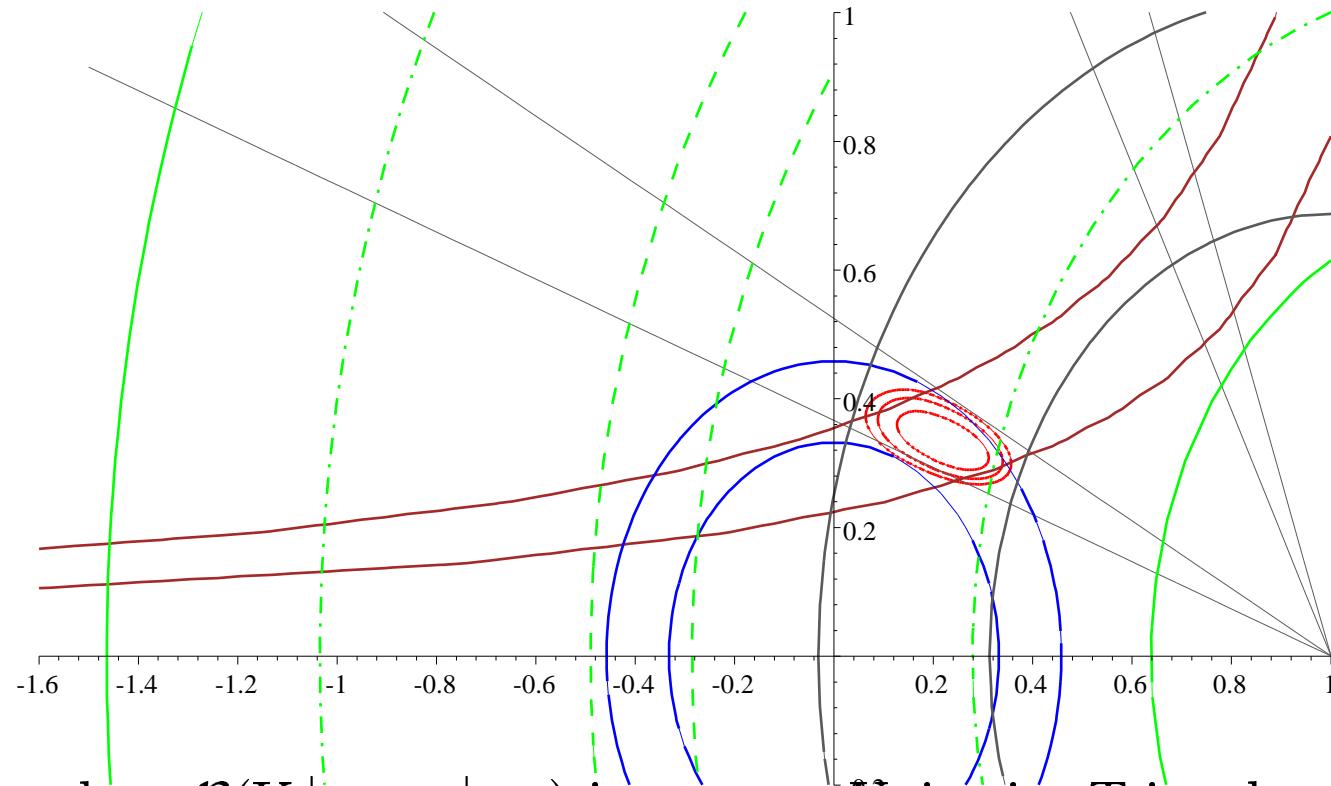
$$\text{SM prediction}^\dagger: \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (0.77 \pm 0.11) \times 10^{-10}$$

The probability that background alone gave rise to the three observed events or to any more signal-like configuration is 0.001.

$$\text{E787 result: } \mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.57^{+1.75}_{-0.82}) \times 10^{-10}$$

<sup>†</sup> Reference: Buchalla& Buras, NPB**548** 309 (1999);  
 Isidori, hep-ph/0307014; Buras, hep-ph/0402112

## Impact of $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ on Unitarity Triangle

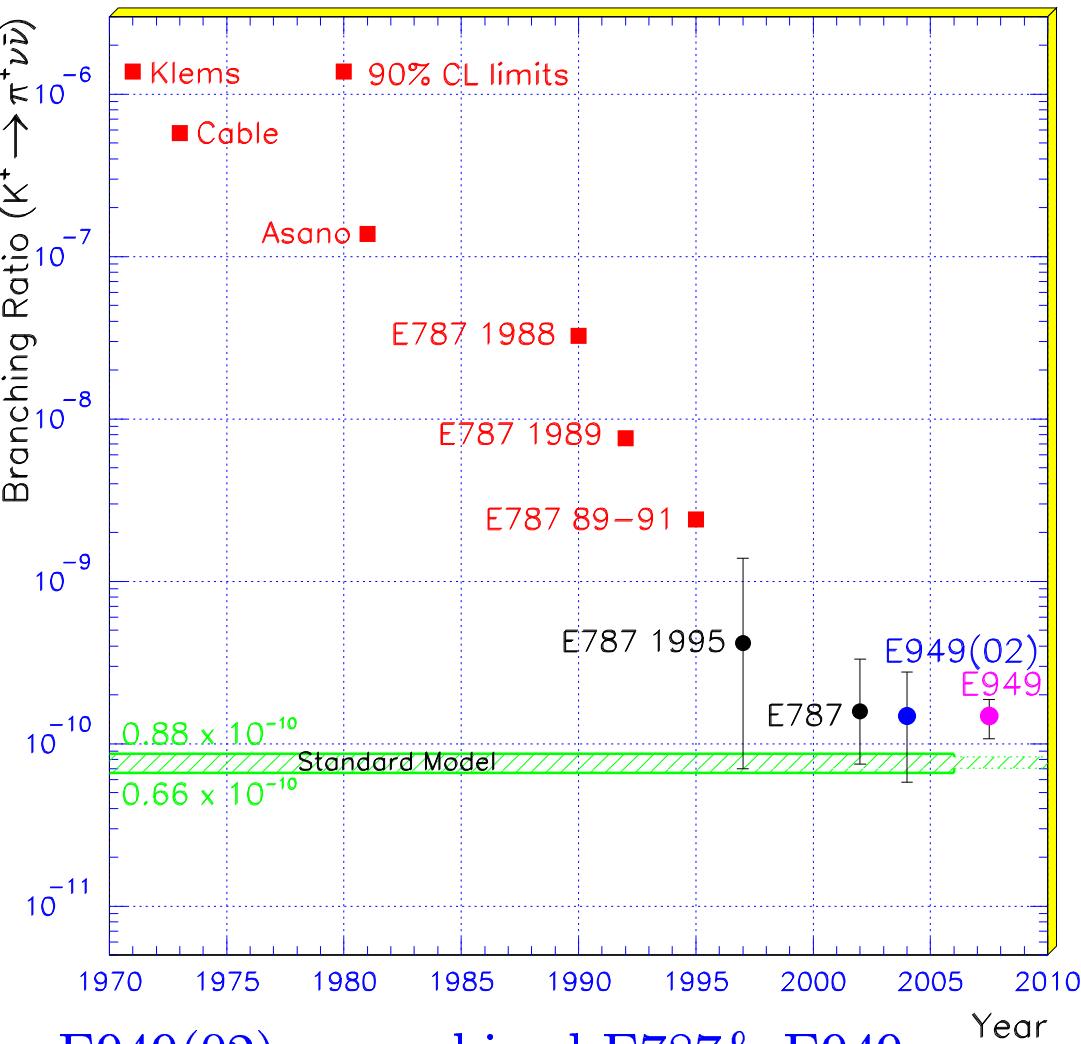


Green lines show  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$  impact on Unitarity Triangle: central value (dashed), 68% interval (dot-dash), 90% interval (solid). Theoretical uncertainty is included.

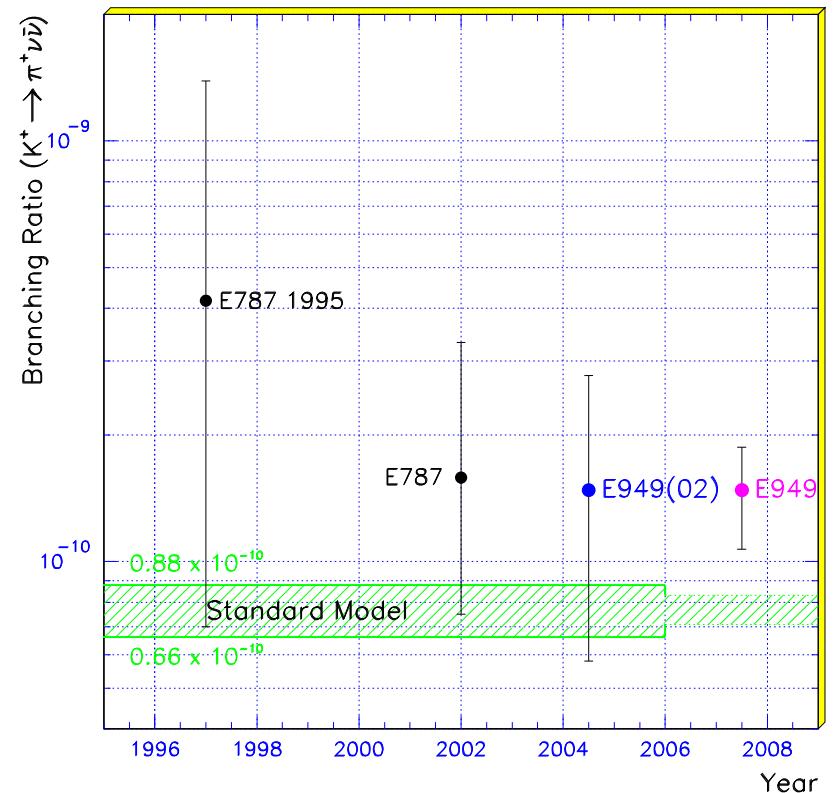
Red ovals show 68%, 90% and 95% areas from other measurements ( $|V_{ub}|$ ,  $\epsilon_K$ ,  $\sin 2\beta$ ,  $\Delta m_d$ ,  $\Delta m_s/\Delta m_d$ )

Provided by Gino Isidori.

## Progress in $K^+ \rightarrow \pi^+ \nu \bar{\nu}$



E949 projection with full running period.



Narrowing of “SM prediction”  
assumes measurement of  $B_s$   
mixing consistent with prediction.

# $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ : Fifteen years ago

PHYSICAL REVIEW D

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1 JUNE 1989

## *CP*-violating decay $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

Laurence S. Littenberg

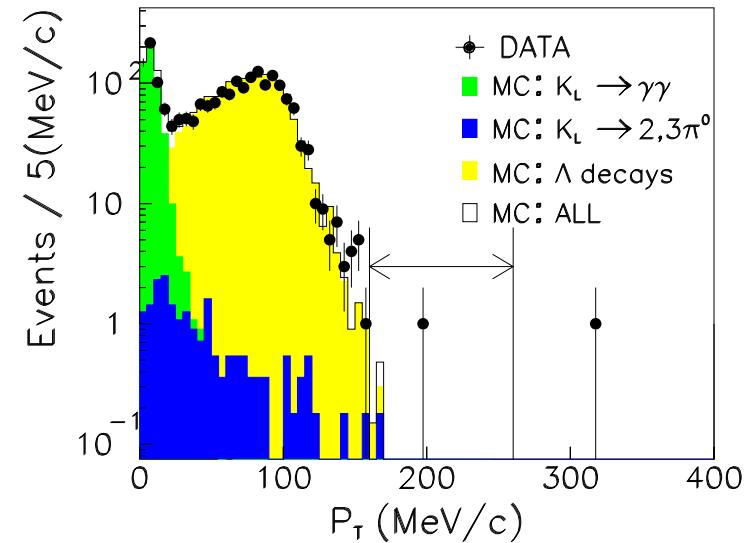
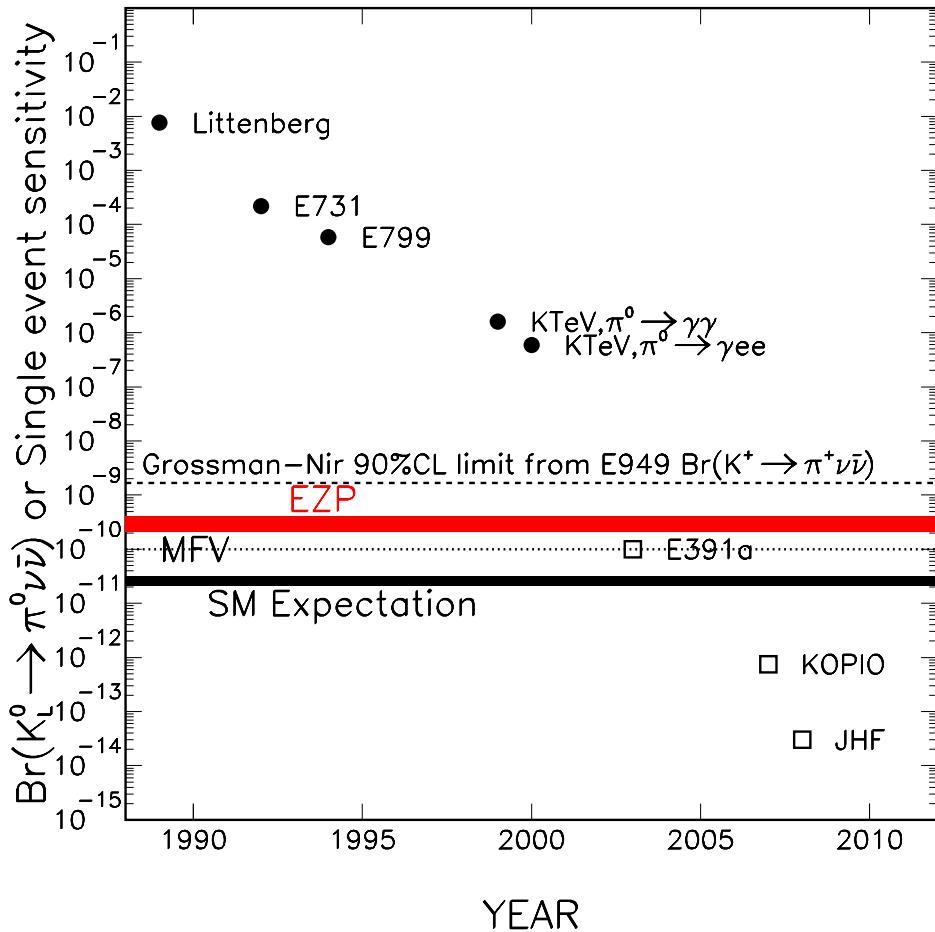
*Department of Physics, Brookhaven National Laboratory, Upton, New York 11973*

(Received 6 January 1989)

The process  $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  offers perhaps the clearest window yet proposed into the origin of *CP* violation. The largest expected contribution to this decay is a direct *CP*-violating term at  $\approx \text{few} \times 10^{-12}$ . The indirect *CP*-violating contribution is some 3 orders of magnitude smaller, and *CP*-conserving contributions are also estimated to be extremely small. Although this decay has never been directly probed, a branching ratio upper limit of  $\sim 1\%$  can be extracted from previous data on  $K_L^0 \rightarrow 2\pi^0$ . This leaves an enormous range in which to search for new physics. If the Kobayashi-Maskawa (KM) model prediction can be reached, a theoretically clean determination of the KM product  $\sin\theta_2 \sin\theta_3 \sin\delta$  can be made.

“Experimentally, the problems are perhaps best represented by the statement that nobody has yet shown that a measurement of this decay is absolutely impossible.” F.J.Gilman, “*CP* Violation in Rare K Decays”, *Blois CP Violations* 1989:481-496

## $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ Progress



KTeV result with “pencil”  
 $K_L^0$  beam (PLB447 (1999) 240).  
 E391a, JHF expts use a  
 similar technique.

## The KOPIO Technique: Work in $K_L^0$ CMS

**Measure everything possible.**

Microbunched  $K_L^0$  beam

Measure  $\gamma$  directions in PR

Measure  $\gamma$  energy in CAL

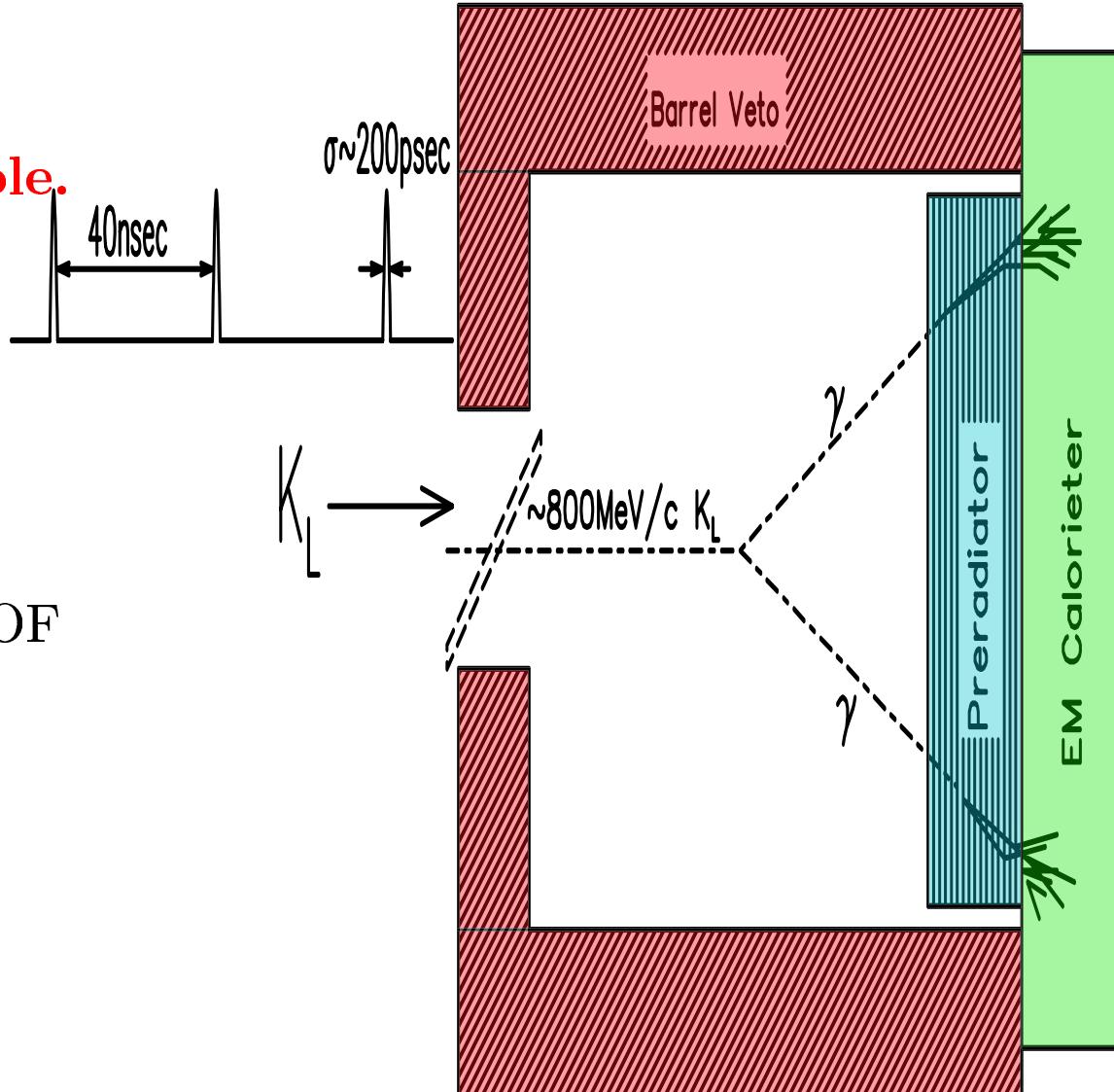
Reconstruct  $\pi^0$  from  $\gamma\gamma$

Measure  $K_L^0$  velocity from TOF

Photon veto

Charged track veto

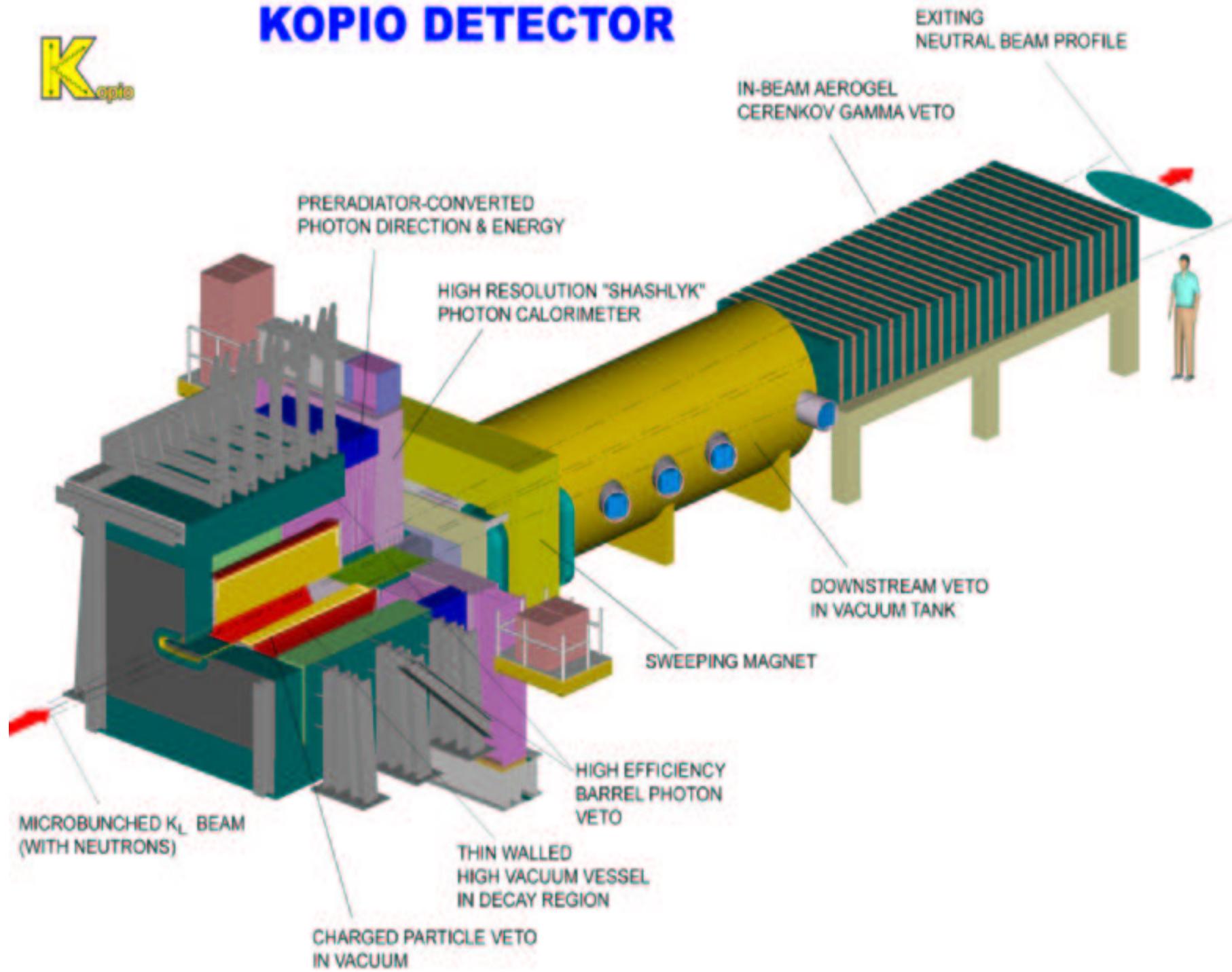
Kinematic veto



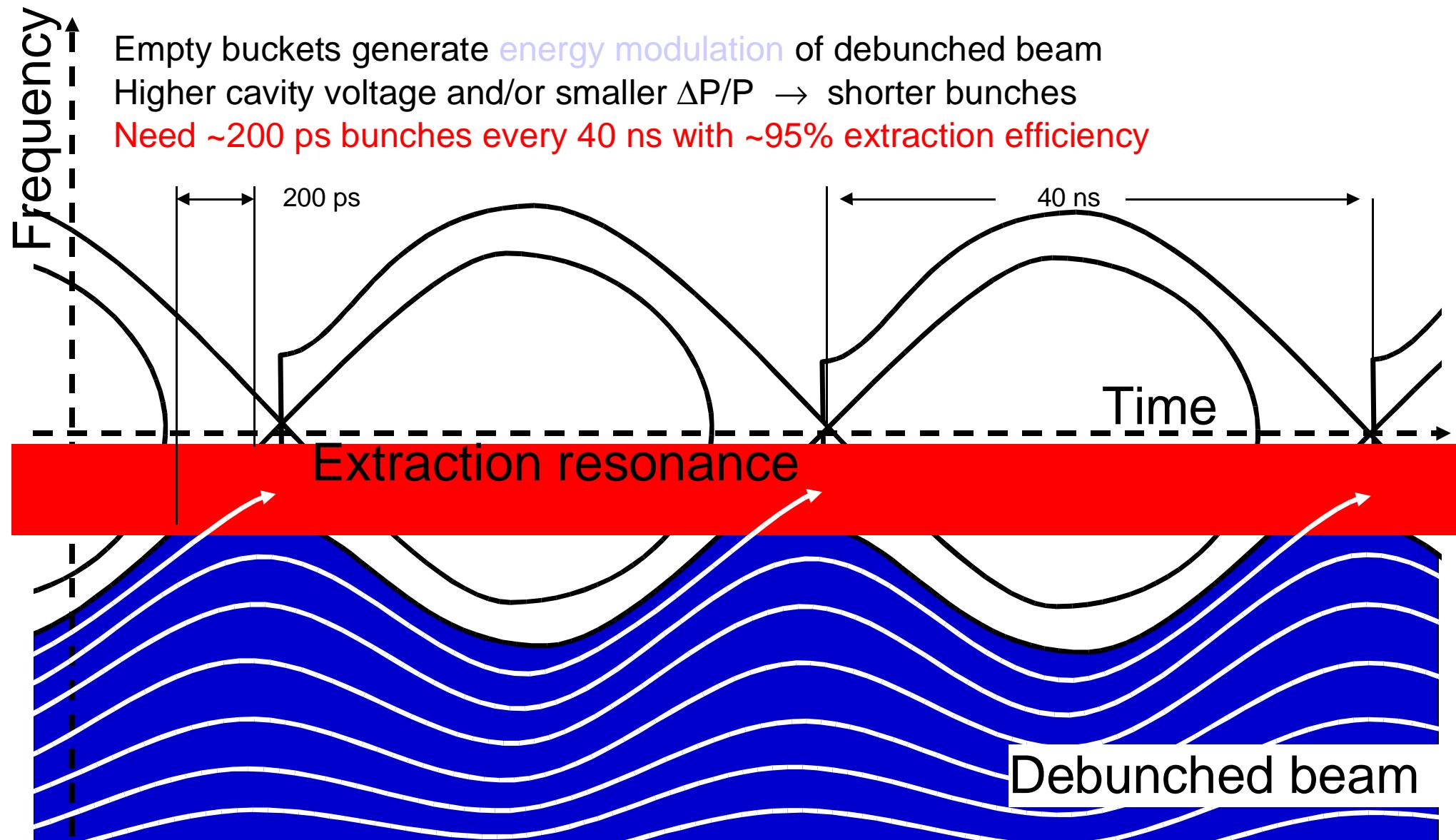
## Some KOPIO performance requirements

Parameter	Minimal Requirement	Expected Performance
$E_\gamma$ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
$\theta_\gamma$ resolution(250 MeV)	25 to 30 mrad	23 mrad
$t_\gamma$ resolution	$100 \text{ ps}/\sqrt{E}$	$50 \text{ ps}/\sqrt{E}$
$x_\gamma, y_\gamma$ resolution(250 MeV)	10 mm	< 1 mm
microbunch width	300 ps	200 ps
microbunch extinction	$10^{-3}$	$< 10^{-3}$
photon veto inefficiency	$\bar{\epsilon}_{\text{E787}}$	$0.3\bar{\epsilon}_{\text{E787}}$
charged veto inefficiency	$10^{-5}(\pi^+), 10^{-4}(\pi^-)$	$< 10^{-5}(\pi^+), < 10^{-4}(\pi^-)$

# KOPIO DETECTOR

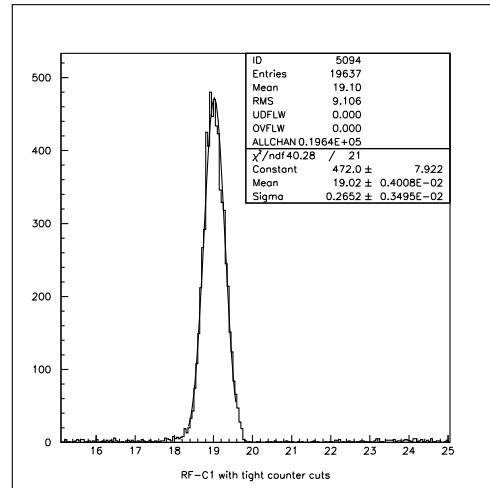


# Micro-bunched slow extraction

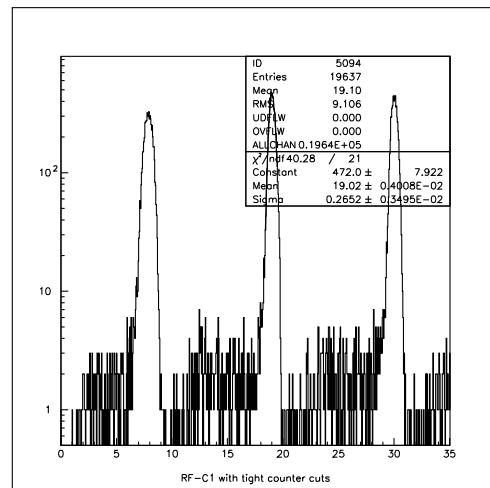


# Microbunch width $\sigma$ and interbunch extinction $E$

**93 MHz RF**

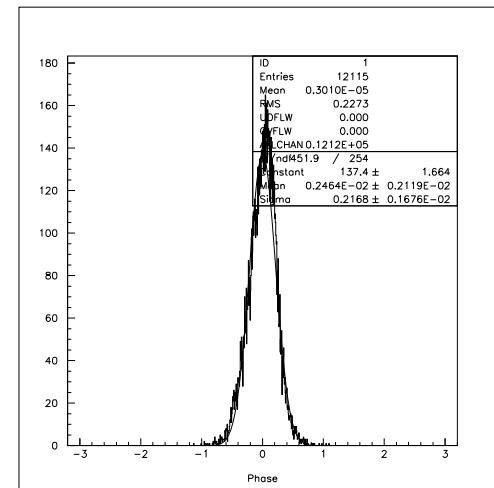


measured  $\sigma = 240$  ps



measured  $E \sim 0.015$

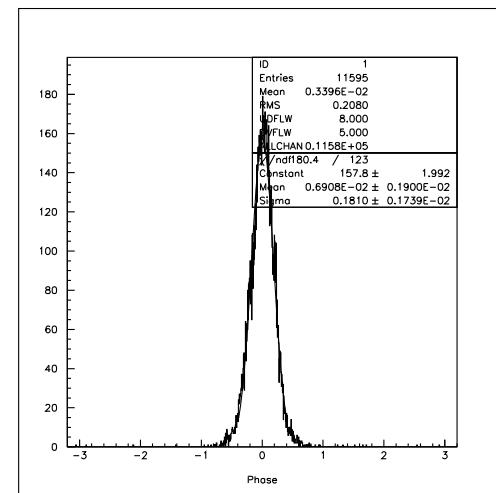
**93 MHz RF**



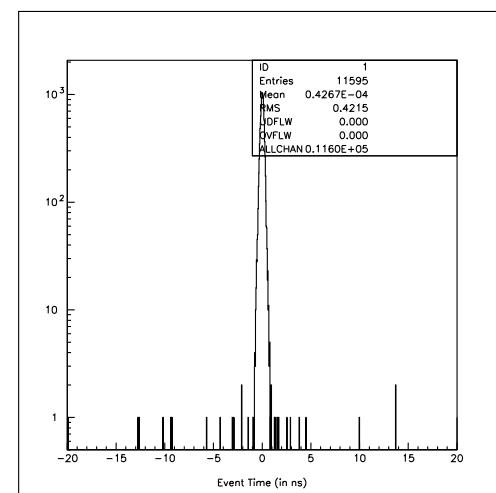
predicted  $\sigma = 215$  ps

Predicted  $E \sim 0.0003$

**25/100 MHz RF**



Predicted  $\sigma = 185$  ps



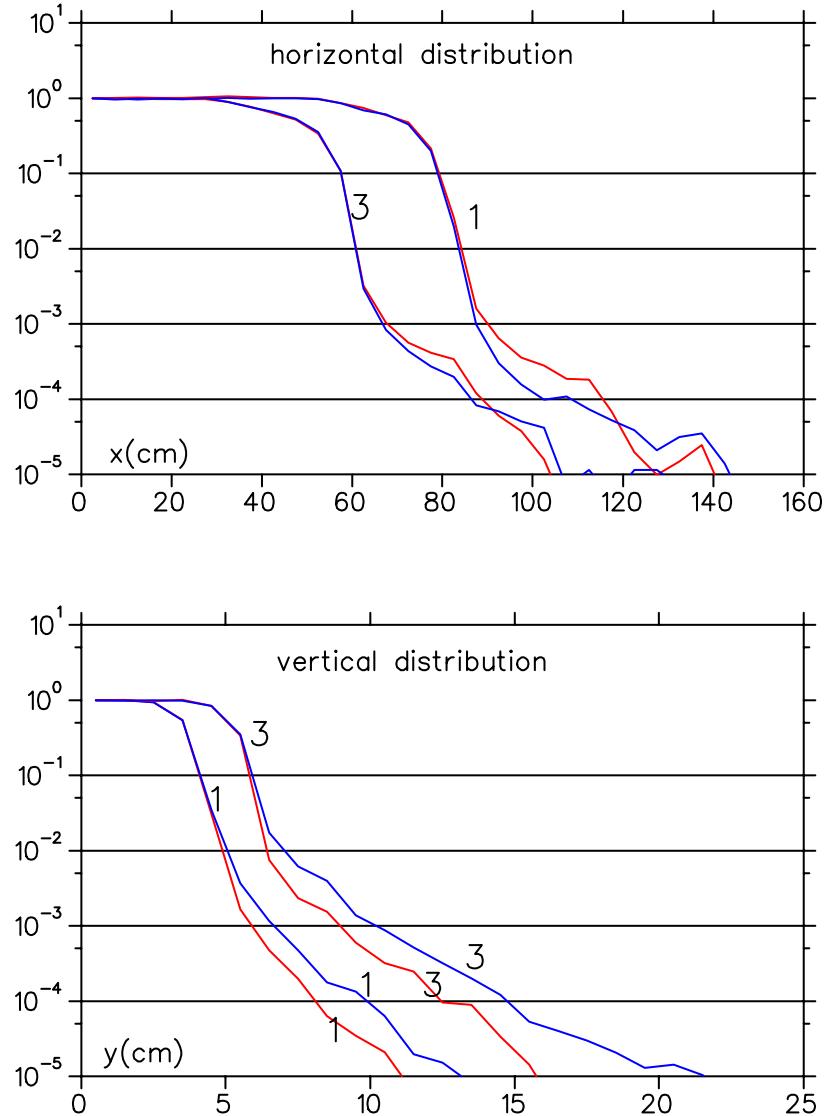
Predicted  $E \sim 0.002$

## KOPIO neutral beam

The central production angle of the KOPIO neutral beam is  $42.5^\circ$ . The aspect ratio is  $100 \times 5 \text{ mrad}^2$  (horiz  $\times$  vert) after passing thru 5 cm of Pb, sweeping magnets and a collimation system.

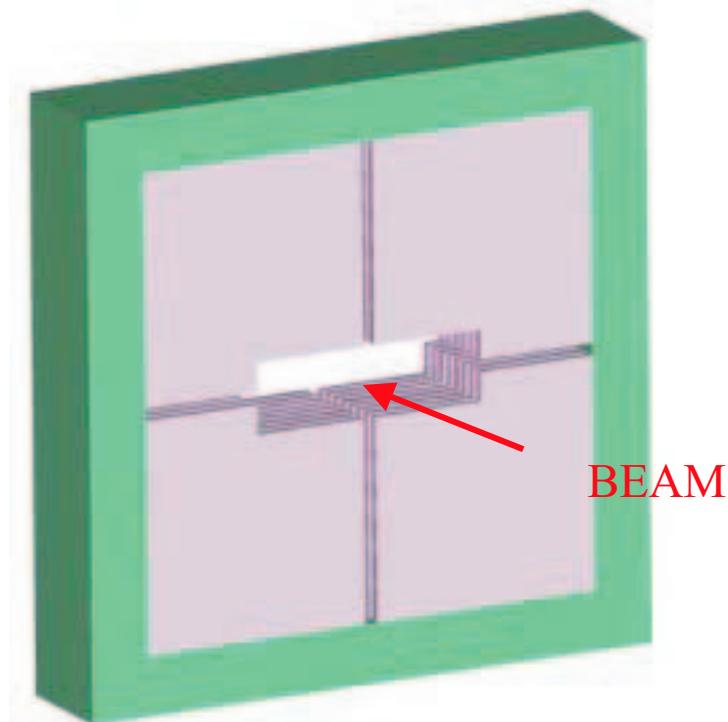
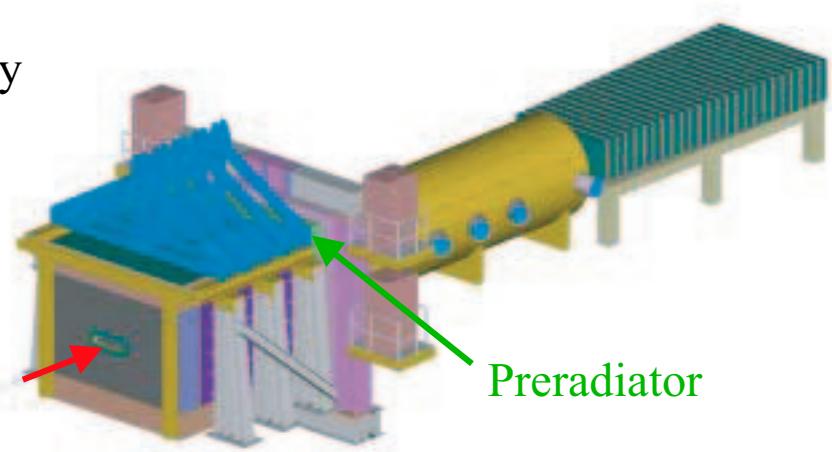
Expect  $\sim 3.5 \text{ K}_L^0$  and  $\sim 600(300) n$  with  $E(n) > 10(262) \text{ MeV}$  per microbunch.

Figure shows the calculated normalized neutron profiles for 2 aspect ratios at the front of the pre-radiator (1400 cm from target). Aspect ratio # 1 is  $100 \times 5 \text{ mrad}^2$ .

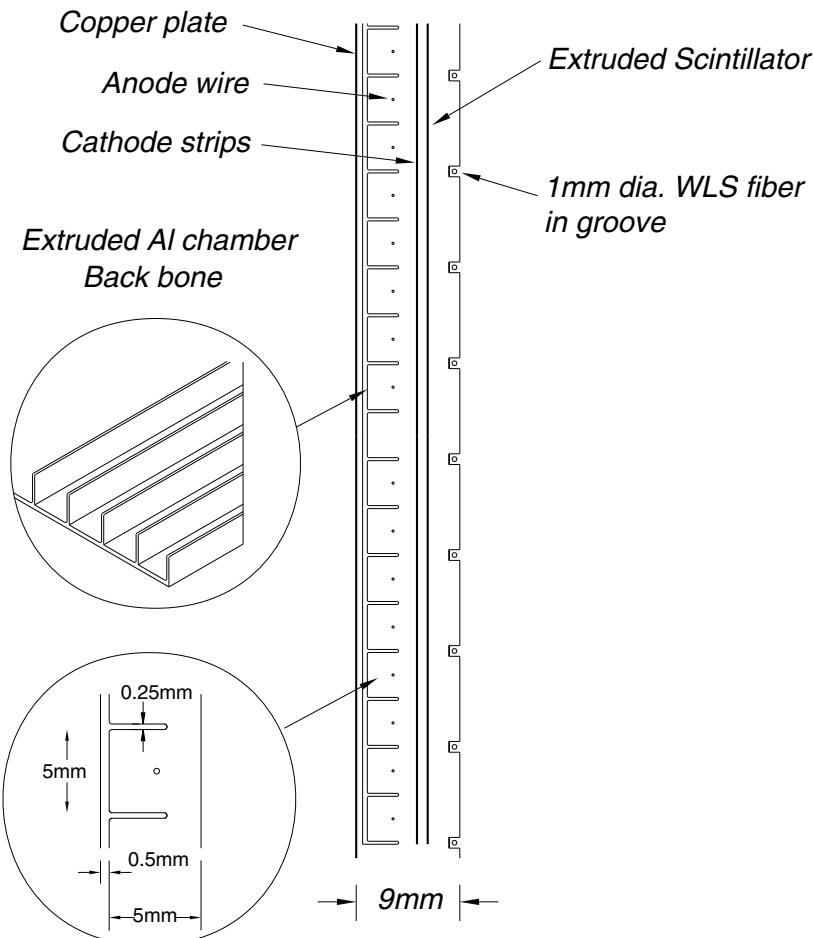


## Preradiator

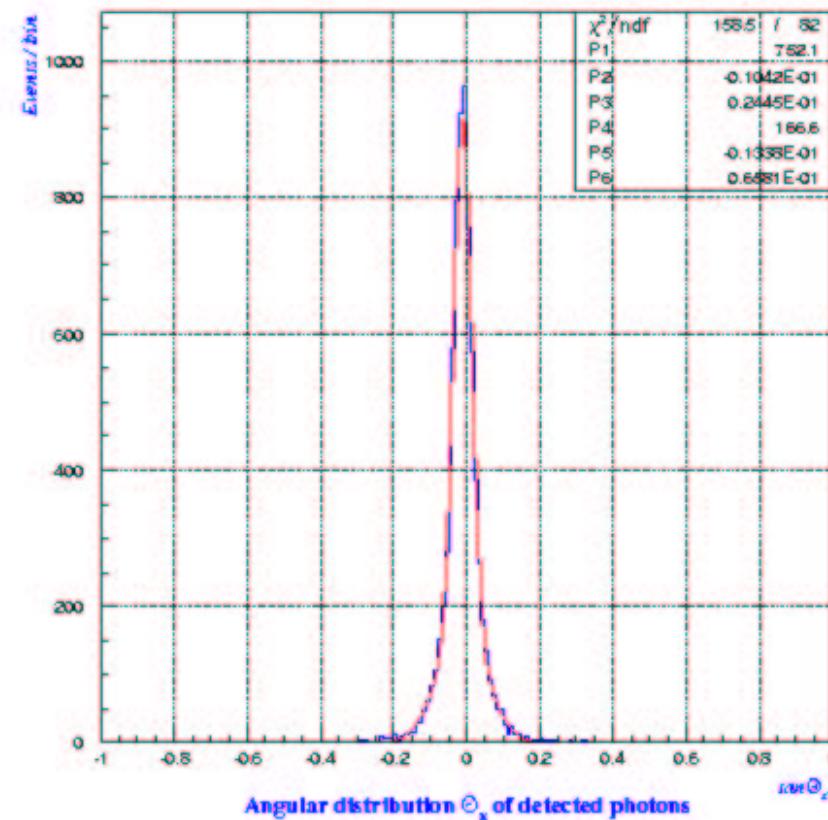
- Measures the direction of rays with 25mr by tracking an e<sup>-</sup>-e<sup>"</sup> pair in the early shower.
- Total radiation length 2 (70 % of converts).
- Consists of 4 2.5x2.5m<sup>2</sup> (2x2m<sup>2</sup> active region) quadrants.
- Each quadrant has 8 modules (construction unit).
- A module has 8 alternating X,Y readout chambers, 9 scintillator, and thin radiator (Cu and Al) planes.
- Each combination (scintillator+chamber+radiator) is 0.03 r.l. thick.
- A photon veto system that is mounted in the same support structure surrounds the active region of the preradiator.
- Chamber electronics will be mounted outside the photon veto system.
- All photo-tubes can easily be accessed for maintenance.



## Preradiator

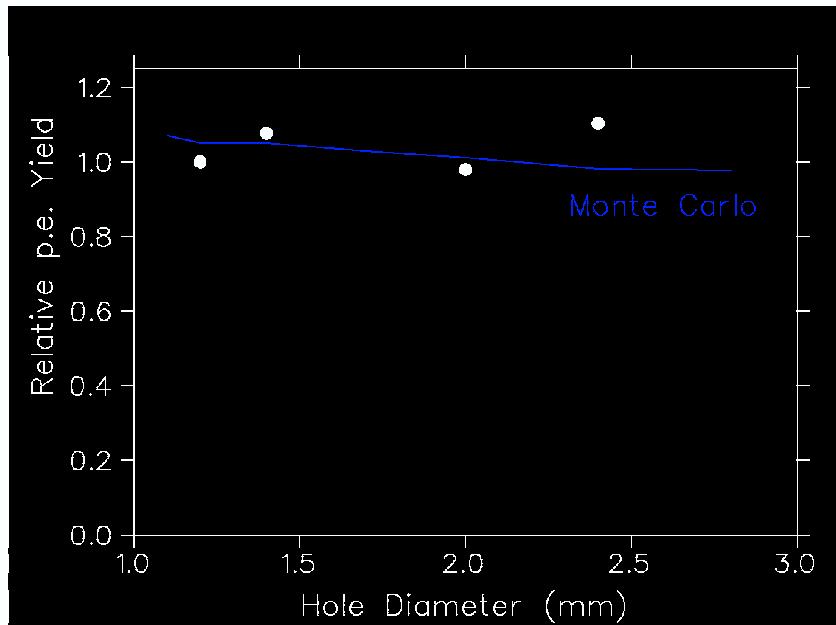


Preradiator angular resolution: 25 mrad at 250 MeV

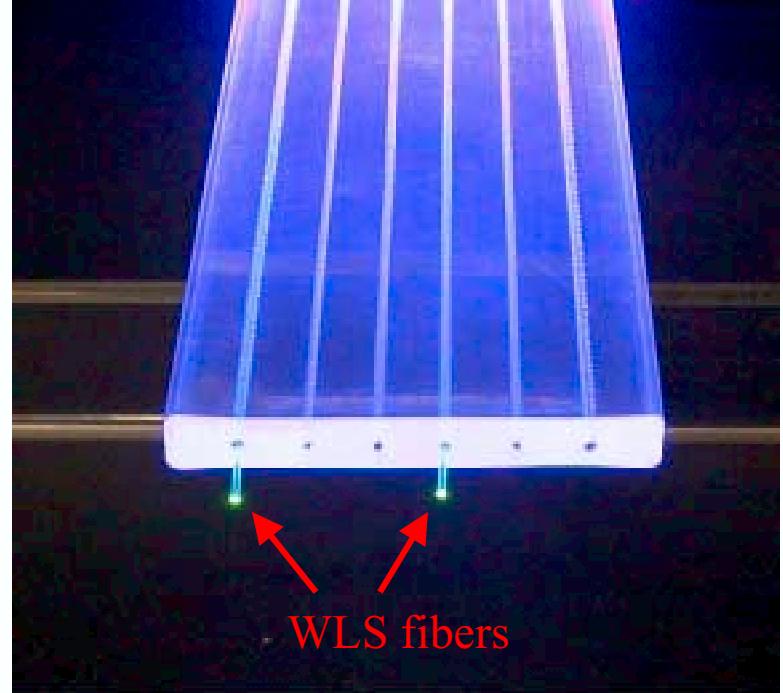


# Scintillator production

- Six hole scintillator has been produced successfully.
- Surface quality and dimension stability will be improved in the near future tests.
- Attenuation length is still shorter than expected, but for the application of fast timing measurement the impact is small.
- No hole diameter dependence.

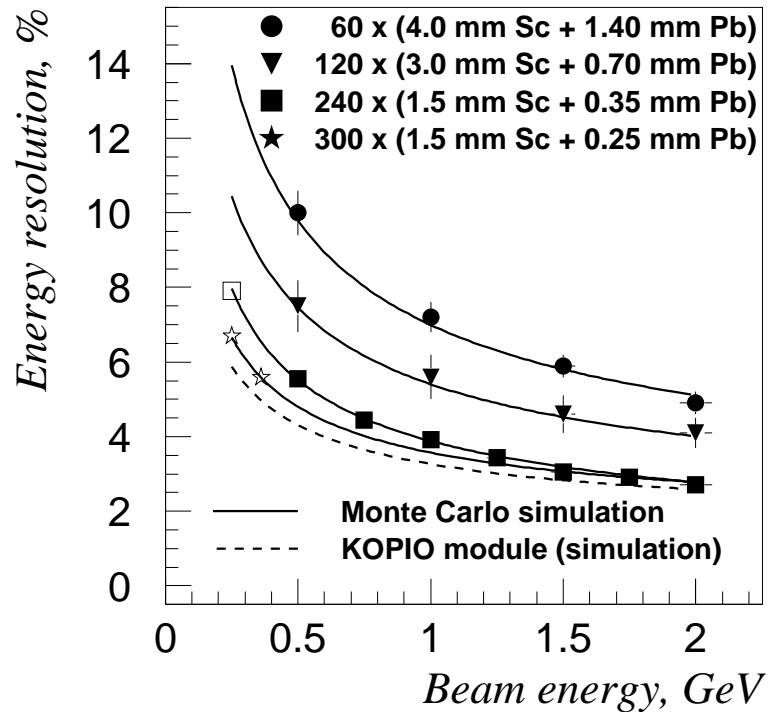
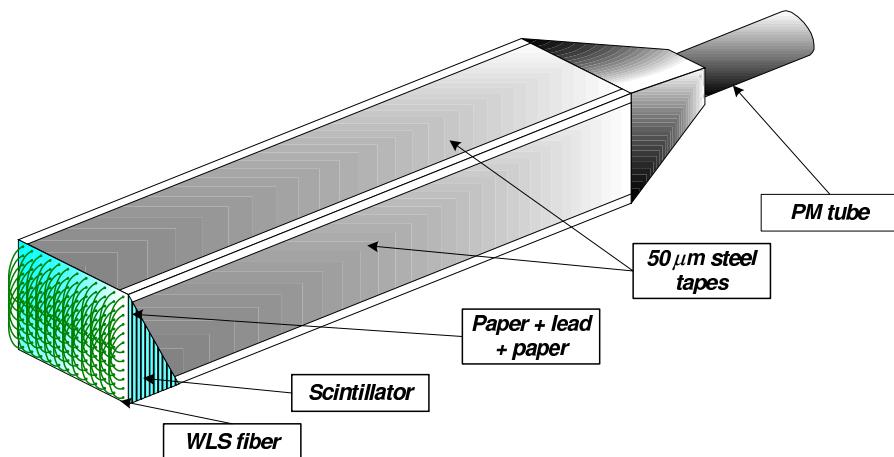


In the real production a sizer box will be installed here.



WLS fibers

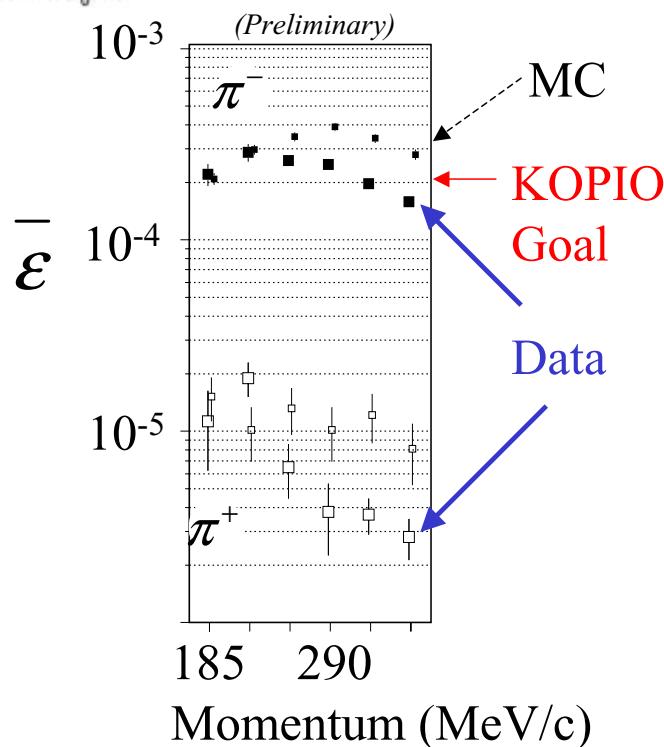
## Shashlyk energy resolution (physics/0310047)



- BNL E865
- ▼ BNL E923 prototype
- KOPIO prototype
- ★ another KOPIO prototype

# Charged Particle Vetoing

Example Background:  $K_L^0 \rightarrow \pi^- e^+ \nu \gamma$



KEK: 1 GeV/c

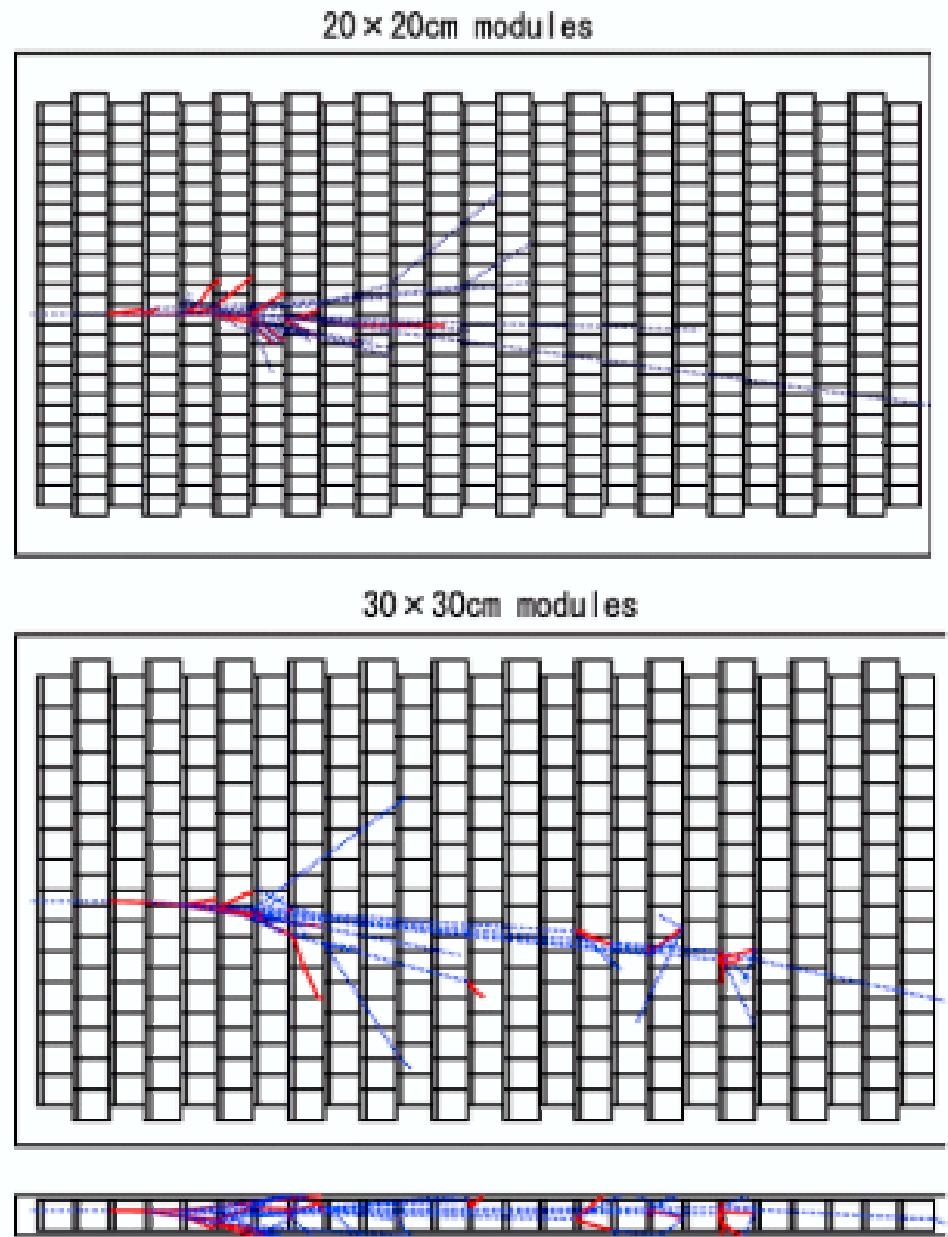
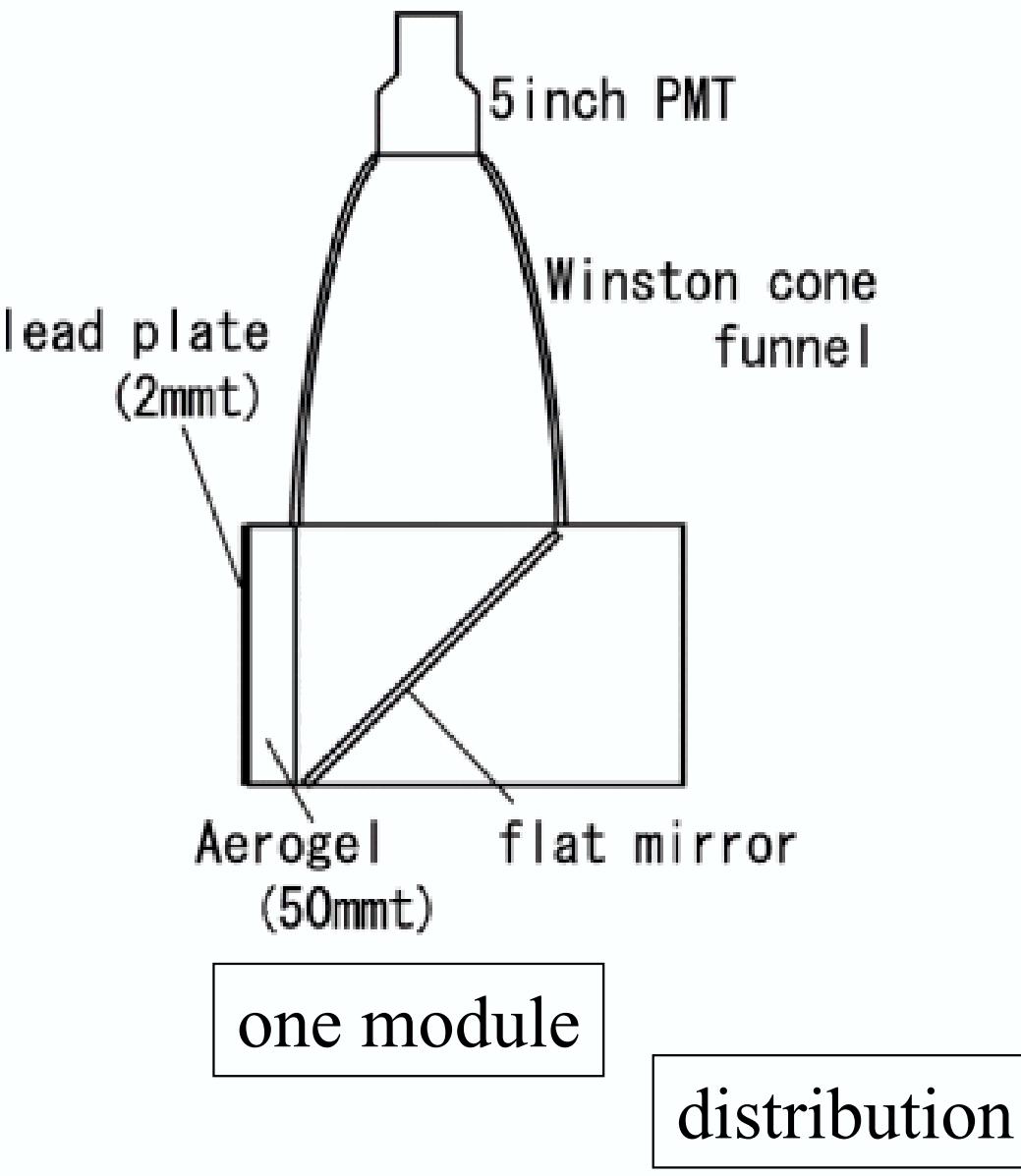
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Particle	$\bar{\epsilon}$
$e^+$	$(3.2 \pm 0.9) \times 10^{-4}$
$\pi^+$	$< 1.6 \times 10^{-5}$
$e^-$	$< 1.3 \times 10^{-4}$
$\pi^-$	$(6.0 \pm 0.6) \times 10^{-4}$

---

NIM A359, 478 (1995)

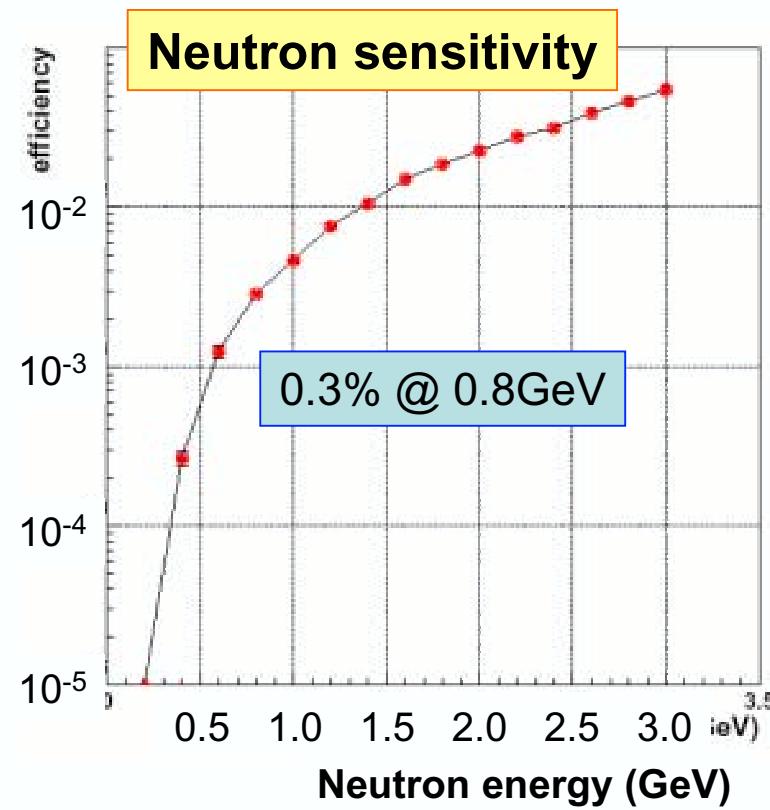
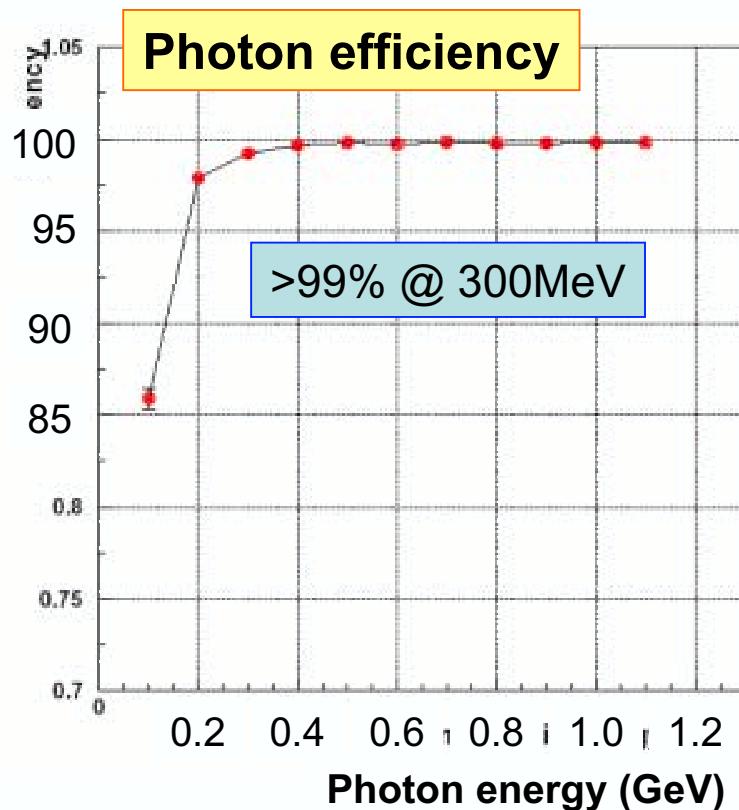
# Fig.1:Base design of catcher



Expected performance with current design

## Photon efficiency / Neutron sensitivity

» Average over +/- 10cm(y), normal incident to Catcher

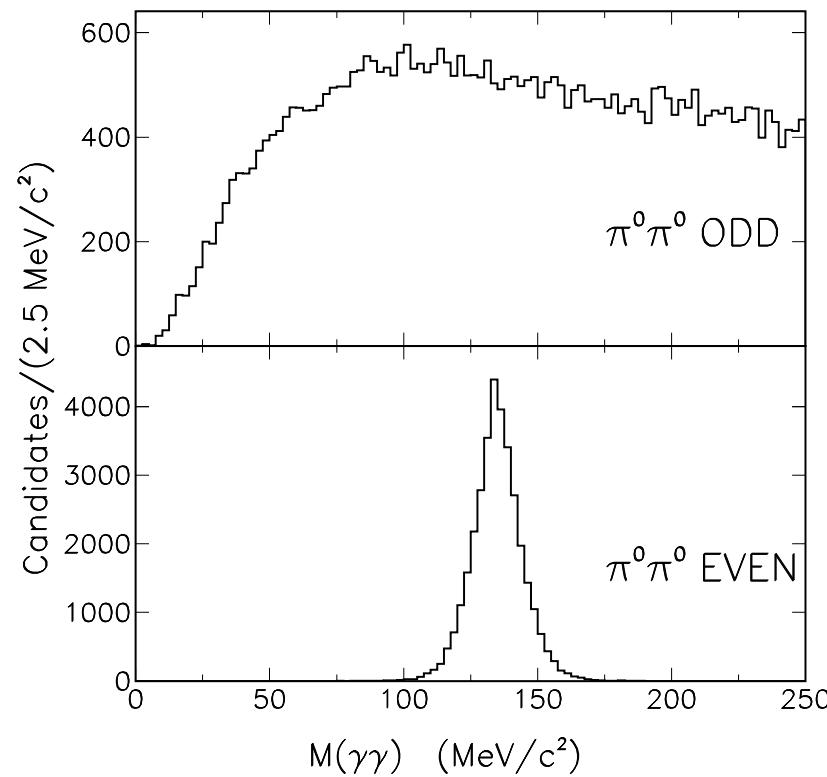
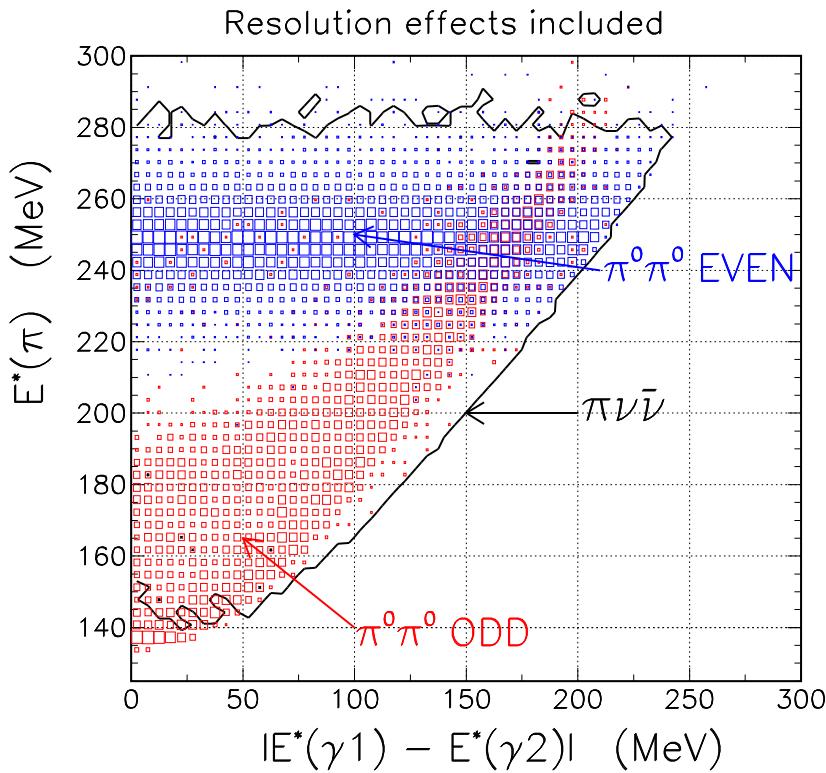


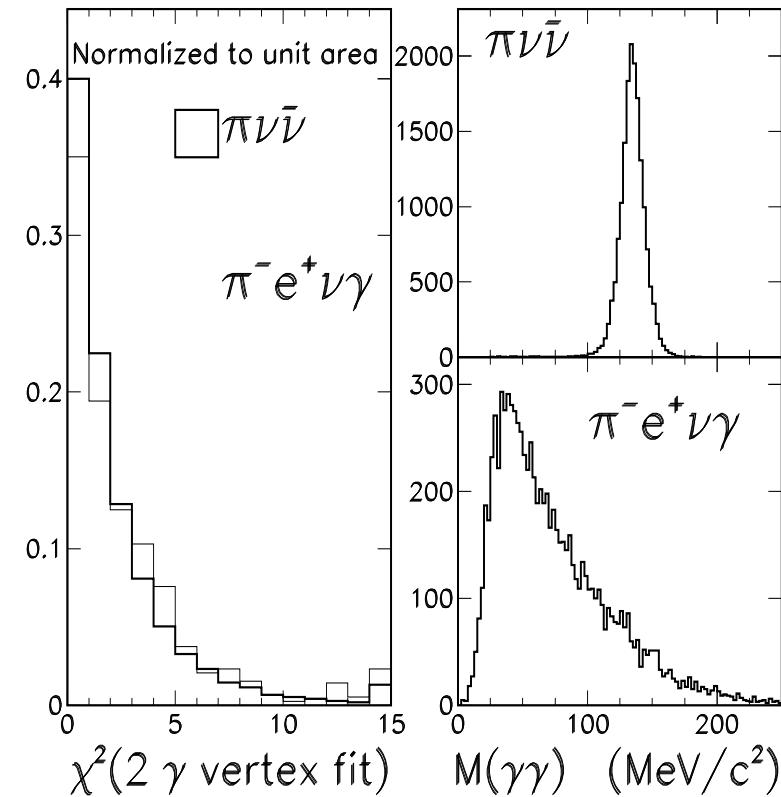
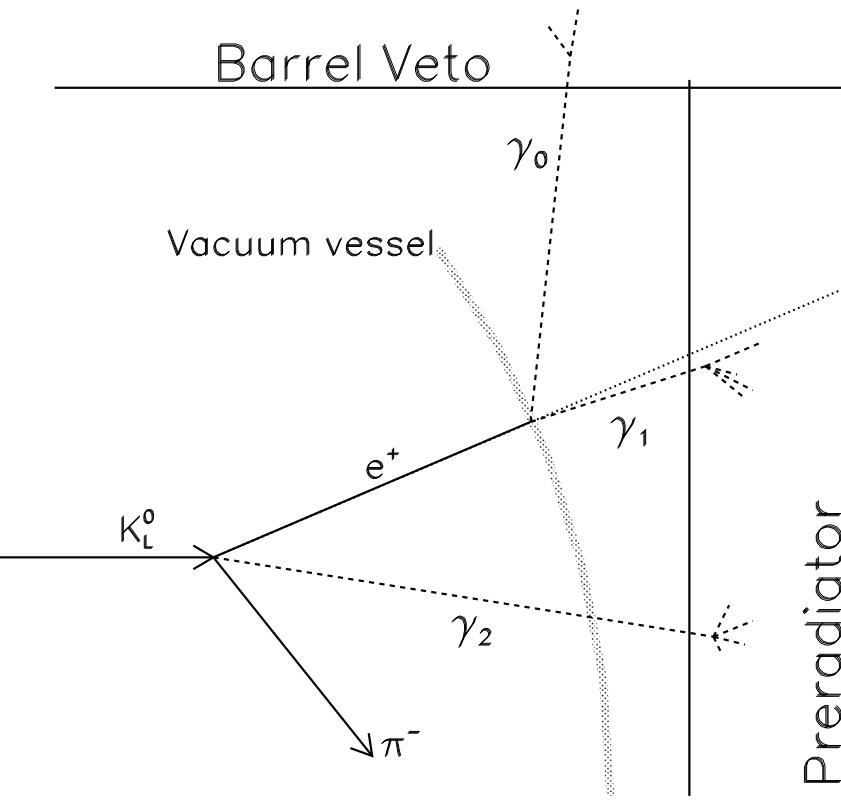
## Background suppression tools

$K_L^0$ Decay	$\mathcal{B}/3 \times 10^{-11}$	Kinematic	Photon veto	Charged veto
$\pi^0\pi^0$ even	$3.1 \times 10^7$	$E_\pi^*$	✓✓	
$\pi^0\pi^0$ odd	$3.1 \times 10^7$	$ E_{1\gamma}^* - E_{2\gamma}^* , M_{\gamma\gamma}$	✓✓	
$\pi^\pm e^\mp \nu\gamma$	$1.2 \times 10^8$	$M_{\gamma\gamma}, \chi^2$	✓	✓
$\pi^+\pi^-\pi^0$	$4.2 \times 10^9$	$E_\pi^*, E_{\text{MISS}}$		✓✓
$\pi^0\pi^\pm e^\mp \nu$	$1.7 \times 10^6$	$E_\pi^*$		✓✓
$\pi^0\pi^0\pi^0$	$7.0 \times 10^9$	$E_\pi^*$	✓✓✓	
$\pi^0\gamma\gamma$	$5.6 \times 10^4$		✓✓	
$\gamma\gamma$	$2.7 \times 10^7$	$M_{\gamma\gamma}, E_\pi^*$		

- even     $\equiv$     both  $\gamma$  from same  $\pi^0$   
 odd     $\equiv$      $\gamma$  from different  $\pi^0$   
 $\chi^2$      $\equiv$      $\chi^2$  of fit of  $\gamma$  3-momenta to a common vertex  
 $M_{\gamma\gamma}$      $\equiv$     2 photon invariant mass  
 $E_i^*$      $\equiv$     energy in  $K_L^0$  rest frame,  $i = \pi^0, \gamma_1, \gamma_2$   
 $E_{\text{MISS}}$      $\equiv$      $E(K_L^0) - E(\gamma_1) - E(\gamma_2)$

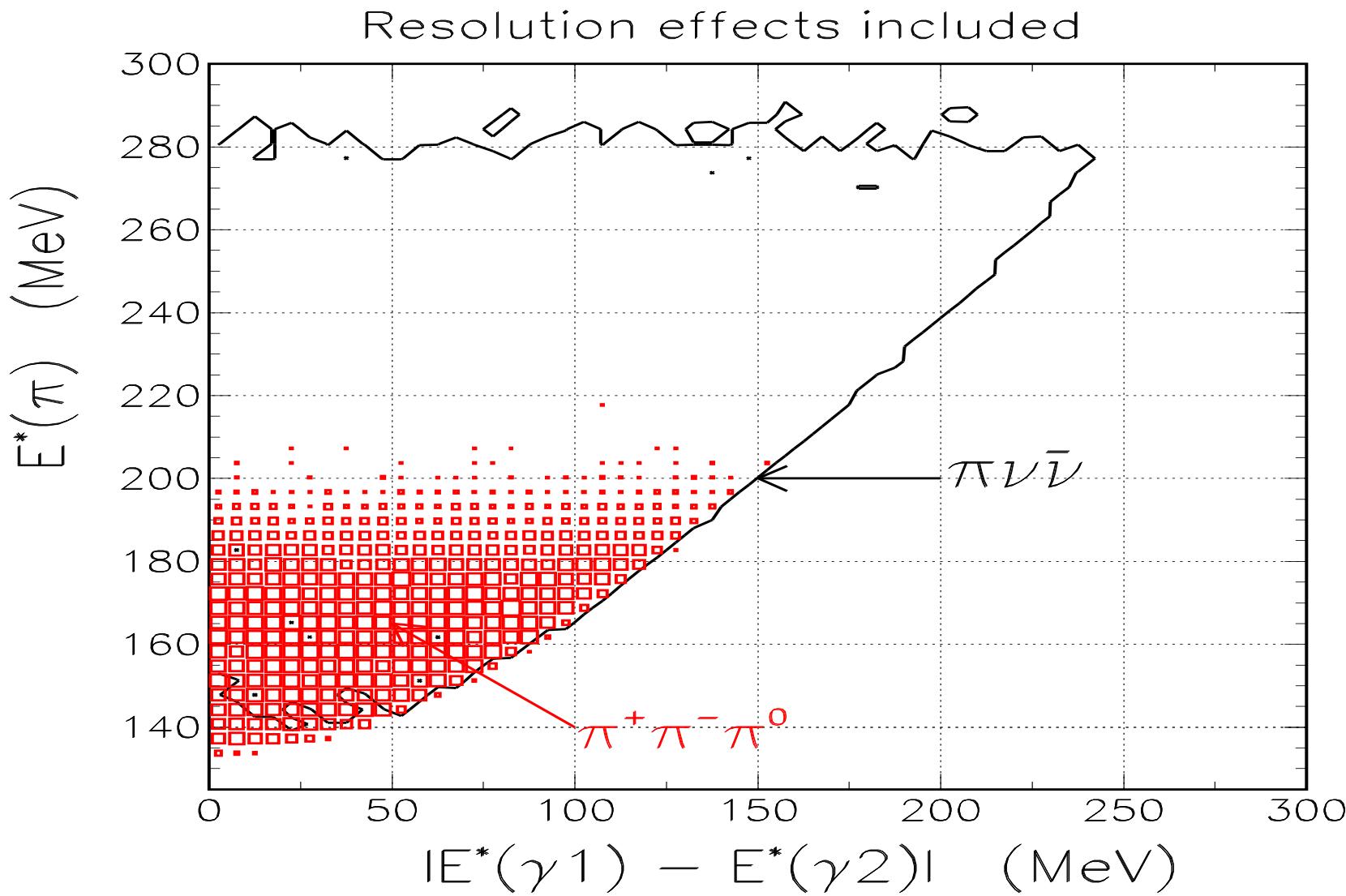
## Kinematic rejection of $K_L^0 \rightarrow \pi^0\pi^0$ background



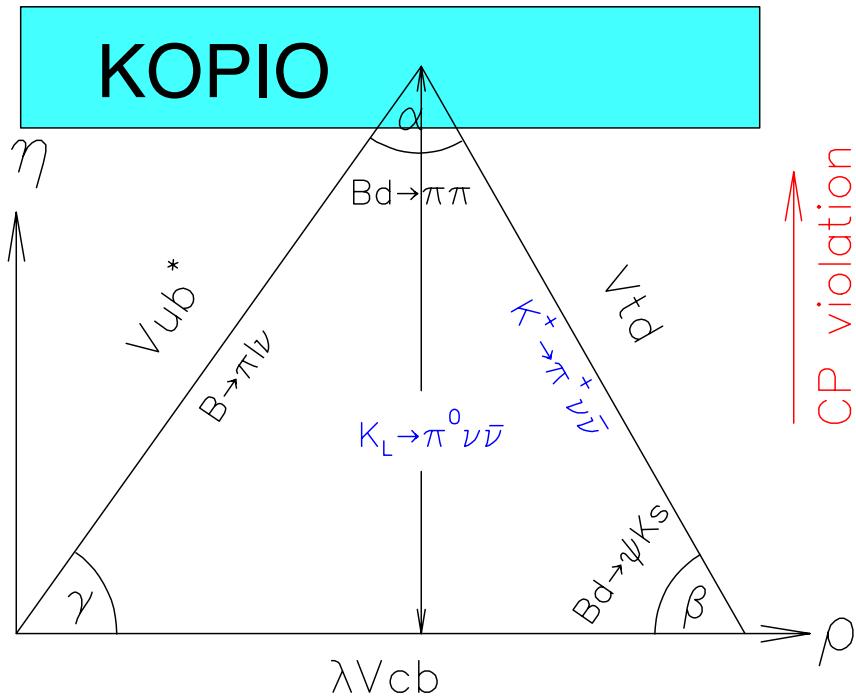
$K_L^0 \rightarrow \pi^- e^+ \nu \gamma_2$  ( $e^+ e^- \rightarrow \gamma_0 \gamma_1$ ) background


Background from  $K_L^0 \rightarrow \pi^\pm e^\mp \nu \gamma$  occurs when the  $e^+$  converts at the vacuum vessel.  $\pi^0$  candidates are formed from  $\gamma_1 \gamma_2$ . For  $e^+ e^- \rightarrow \gamma_0 \gamma_1$ ,  $p(\gamma_1) \approx p(e^+)$  and  $p(\gamma_0) \approx p(e^-)$ . Modest rejection possible from lower energy  $\gamma_0$  and increased  $\chi^2$  from slight change of  $\gamma_1$  from the original  $e^+$  direction.

## Kinematic rejection of $K_L^0 \rightarrow \pi\pi\pi$ backgrounds



## KOPIO signal and background estimates

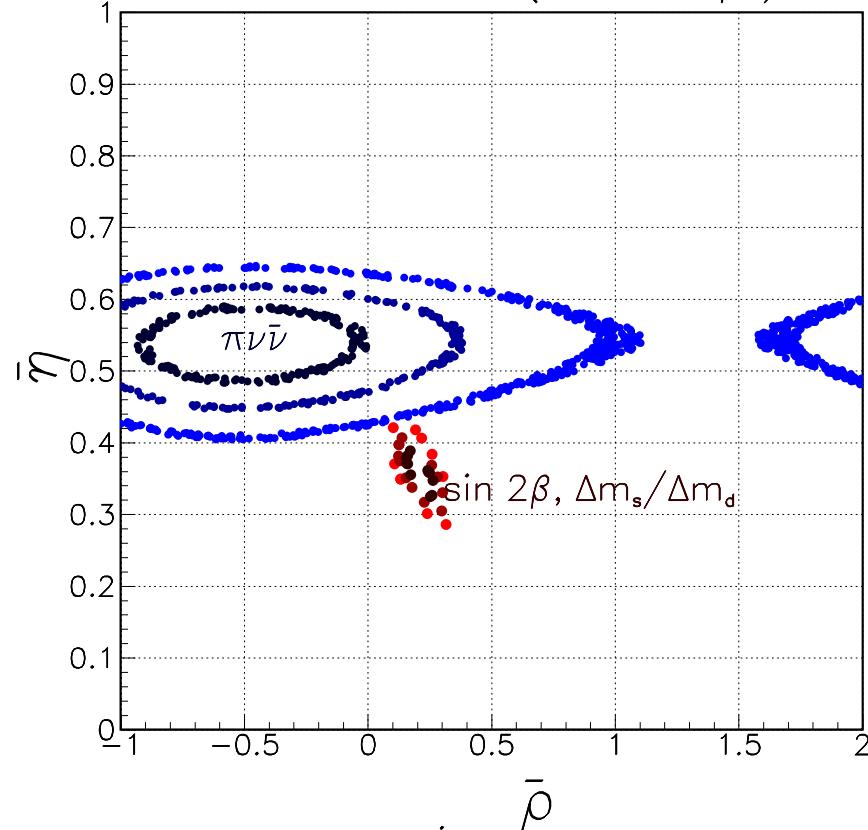


$\Delta\mathcal{B}/\mathcal{B} \approx 20\%$  or  
 $\Delta\eta/\eta \approx 10\%$  at S/B=2

Process	Events
$K_L^0 \rightarrow \pi^0 \bar{\nu}$ at SM rate	40
$K_L^0 \rightarrow \pi^0 \pi^0$	12.4
$K_L^0 \rightarrow \pi^\pm e^\mp \nu \gamma$	4.5
$K_L^0 \rightarrow \pi^- \pi^+ \pi^0$	1.7
$K_L^0 \rightarrow \pi^\pm e^\mp \nu$	0.02
$K_L^0 \rightarrow \gamma \gamma$	0.02
$\Lambda \rightarrow \pi^0 n$	0.01
Interactions ( $nN \rightarrow \pi^0 X$ )	0.2
Accidentals	0.6
Total Background	19.5

## Possible impact of E949,KOPIO $K \rightarrow \pi\nu\bar{\nu}$ measurements

$n\sigma$  contours,  $n = 1, 2, 3$  (E949 expt) 2\*SM



### Assumptions:

- E949 & KOPIO run for approved running period.
- $K \rightarrow \pi\nu\bar{\nu}$  rates at twice SM expectation
- $\Delta m_s = 17.0 \pm 1.7 \text{ ps}^{-1}$
- $\sin 2\beta = 0.70 \pm 0.02$

## Summary and outlook for $K \rightarrow \pi \nu \bar{\nu}$

**E949** has observed an additional  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  candidate and measures  $\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (1.47^{+1.30}_{-0.89}) \times 10^{-10}$  for the combined data of E787 and **E949**. The result is consistent with the current Standard Model prediction.

**E949** analysis of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  for momenta  $P(\pi^+) < 195 \text{ MeV}/c$  in progress.

**E949:** Approved (1999), HEP at AGS halted(2002), other funding sources sought...

Another stopped- $K^+$  experiment to measure  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  under consideration at KEK in Japan.  $K^+$  decay-in-flight experiments under consideration at FNAL and CERN.

E391a: ( $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$  at KEK) Began stable data-taking in March 2004

**KOPIO:** Approved by NSF(2003), construction start in 2005, in need of zealous collaborators.

These experiments would be able to test the precise predictions for  $K \rightarrow \pi \nu \bar{\nu}$  branching fractions.

**Extras**

$$\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = K_+ \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 + \left[ \text{Re} \lambda_c \frac{P_0}{\lambda} + \text{Re} \lambda_t \frac{X}{\lambda^5} \right]^2 \right)$$

$$\mathcal{B}(K_L^0 \rightarrow \pi^0 \nu \bar{\nu}) = K_0 \left( \left[ \text{Im} \lambda_t \frac{X}{\lambda^5} \right]^2 \right)$$

$$\lambda_i \equiv V_{is}^* V_{id}$$

$$K_+ \equiv r_+ B$$

$$K_0 \equiv r_0 B \tau(K_L^0) / \tau(K^+)$$

$$B \equiv 3\alpha^2 \mathcal{B}(K^+ \rightarrow \pi^0 e^+ \nu) / 2\pi^2 \sin^4 \theta_W$$

$$X \equiv X(x_t) \equiv \frac{x_t}{8(x_t - 1)} \left( x + 2 + \frac{3x - 6}{x - 1} \ln x \right)$$

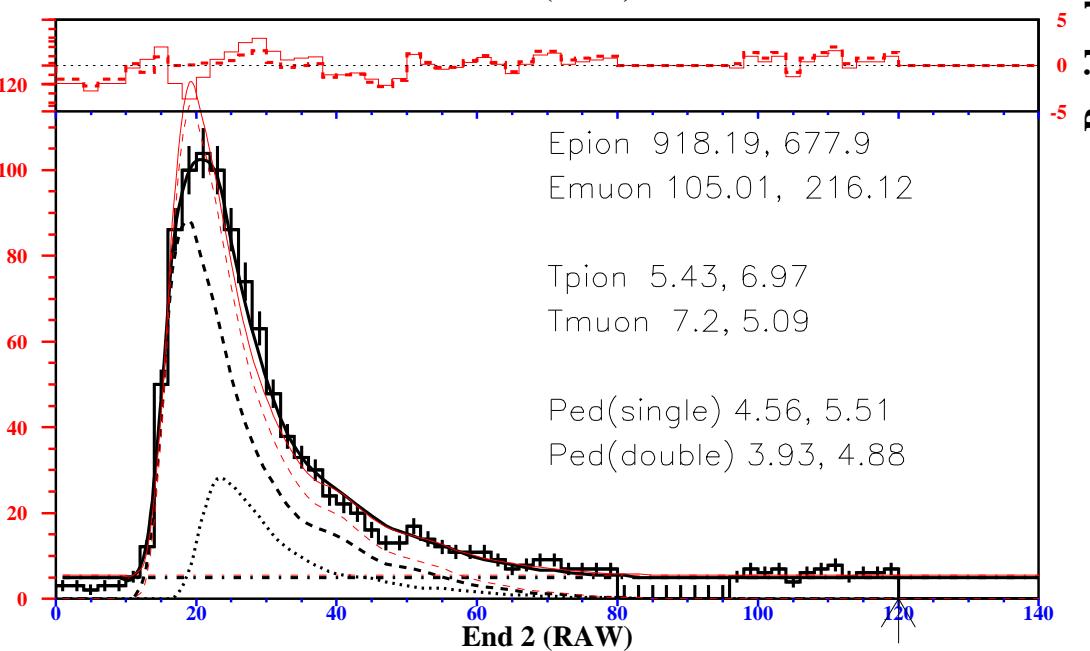
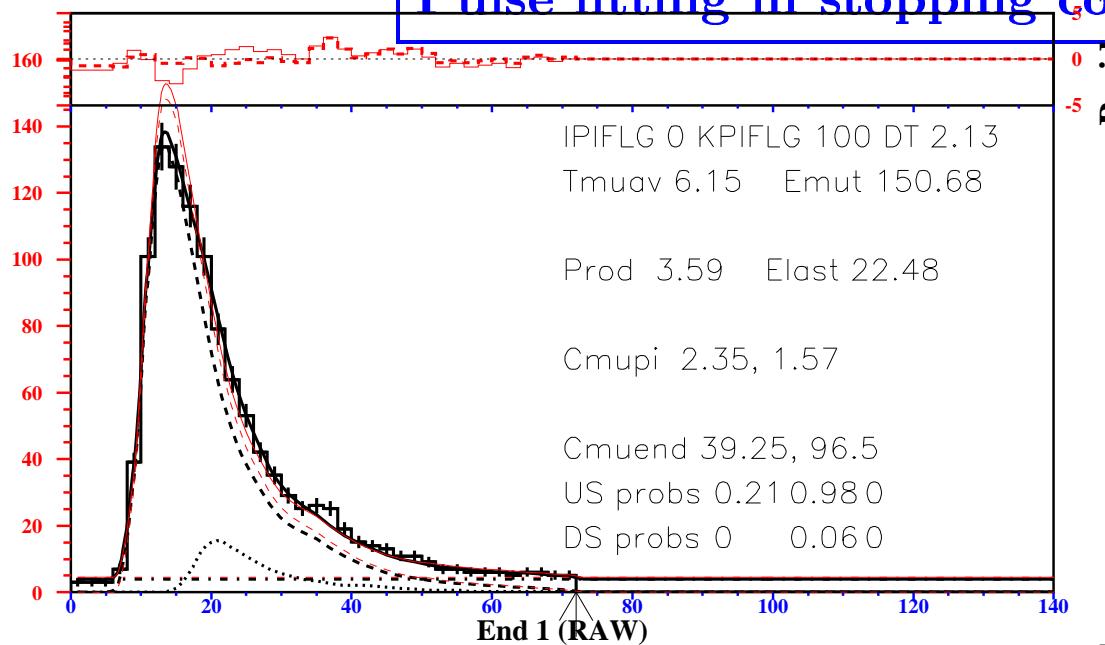
$$x_t \equiv (m_t/m_W)^2$$

$$r_+ = 0.901$$

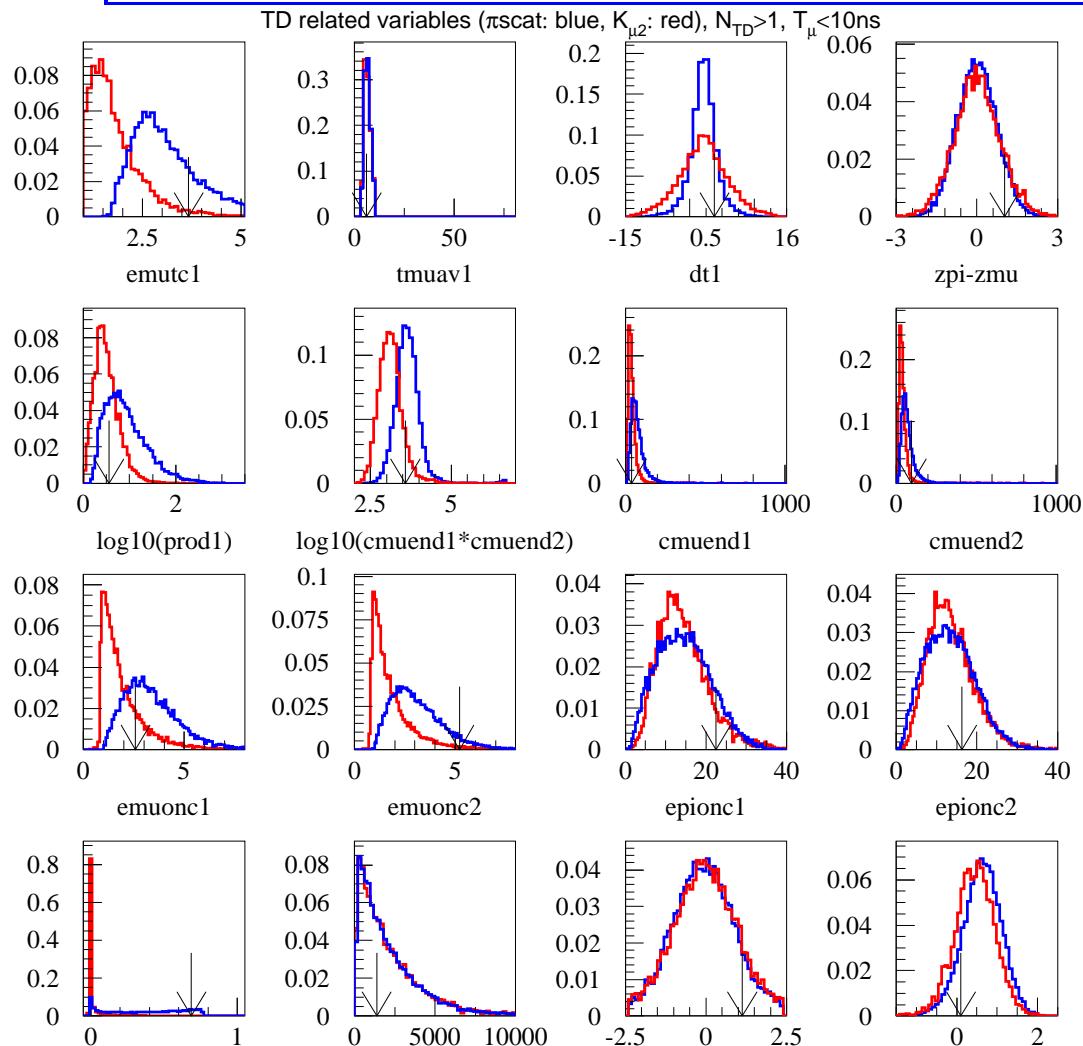
$$r_0 = 0.944$$

$$P_0 = 0.40 \pm 0.06 \text{ (charm)}$$

## Pulse fitting in stopping counter



## Compare TD properties of candidate with $\pi^+$ and $\mu^+$ samples



Quantities related to pion particle identification from TD variables. Events with similar background rejection and fitted muon time  $< 10$  ns are selected. The pion signal (blue) and the muon background (red) are shown in the same plots. The arrows indicate the positions of the candidate event.

## Remind: E949-2002 beam conditions were not optimized

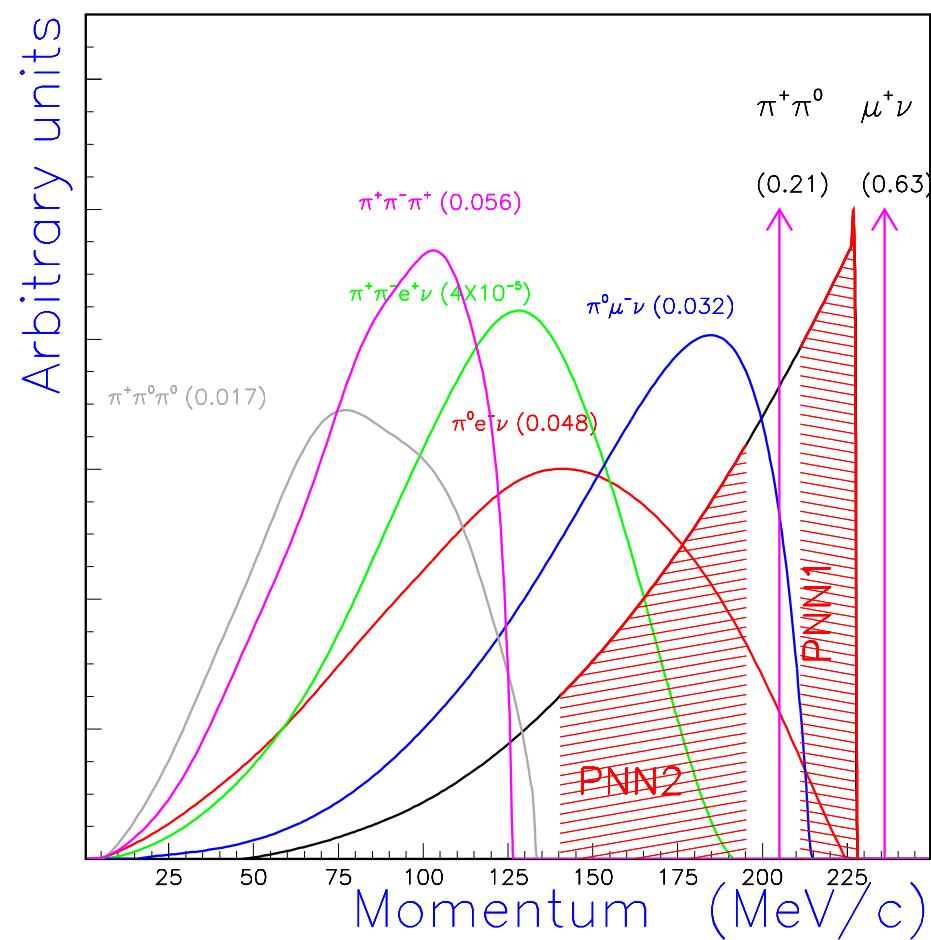
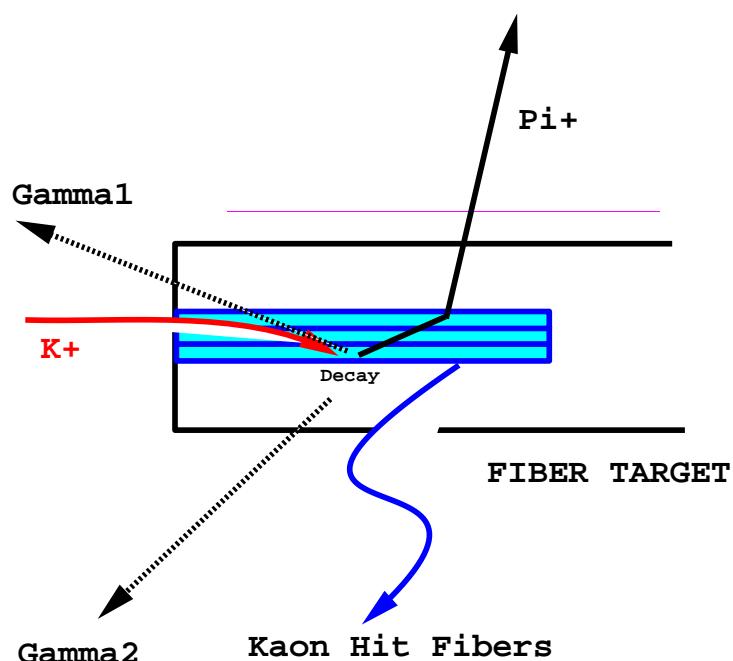
- a failure of the AGS power supply
- reduced operating voltage of one of the DC separators
- 12 weeks

The conditions will be improved in the next run.

		E787	E949-'02	E949 optimized
AGS energy	GeV	24	22	24
beam spill	sec	2.2	2.2	4.1
cycle	sec	4.2	5.4	6.4
duty factor	%	52	41	64
$K^+/\pi^+$		4	3	4
$N_K$ in the spill		1.8	2.5	5.0
$N_K$	MHz	0.8	1.2	1.2
rates in the detector	M		$\times 2$	$\times 2$ or less
beam time	weeks		12	$\geq 60$

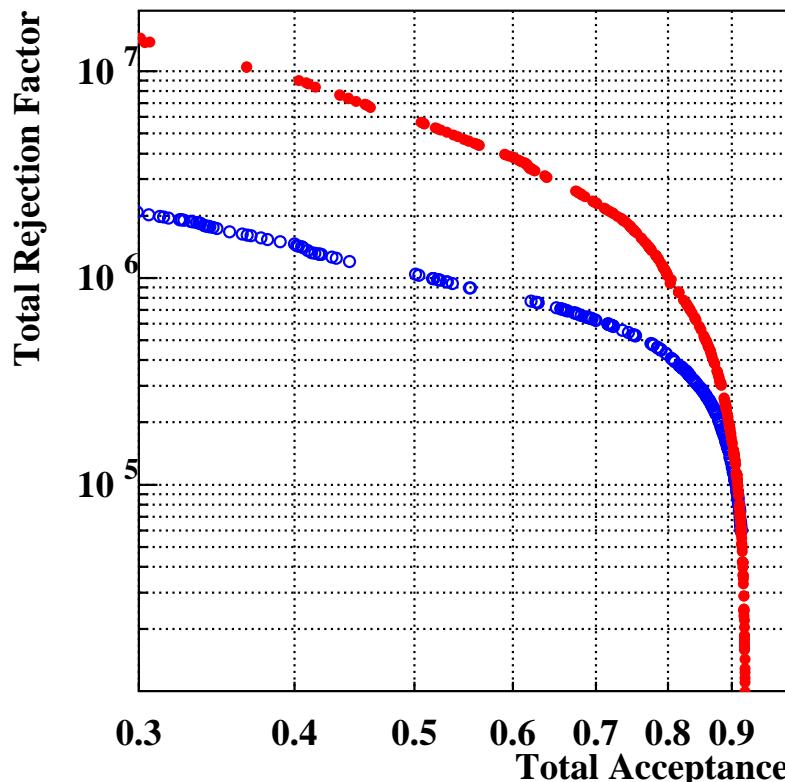
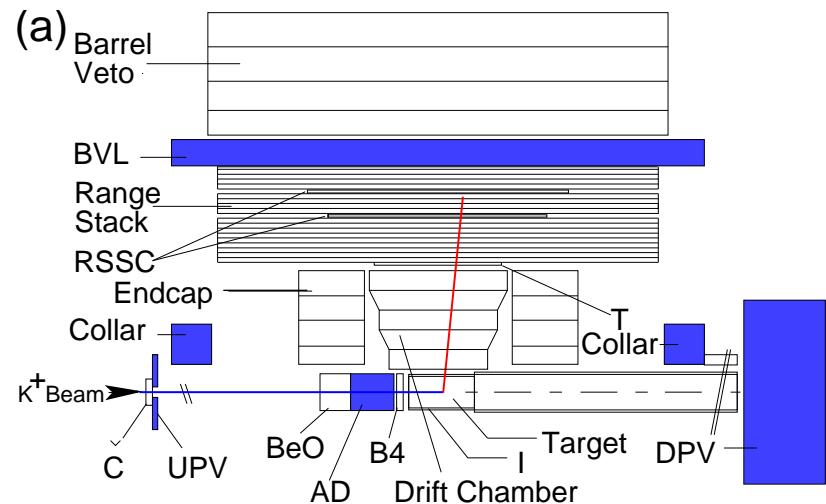
## PNN2: $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ below $K^+ \rightarrow \pi^+ \pi^0$ peak

- More phase space than PNN1
- Less loss due to  $\pi^+ N$  interactions
- $P(\pi^+) = (140, 195) \text{ MeV}/c$  probes more of  $K^+ \rightarrow \pi^+ \nu \bar{\nu}$  spectrum
- Main background mechanism is  $K^+ \rightarrow \pi^+ \pi^0$  followed by  $\pi^+$  scatter in target.



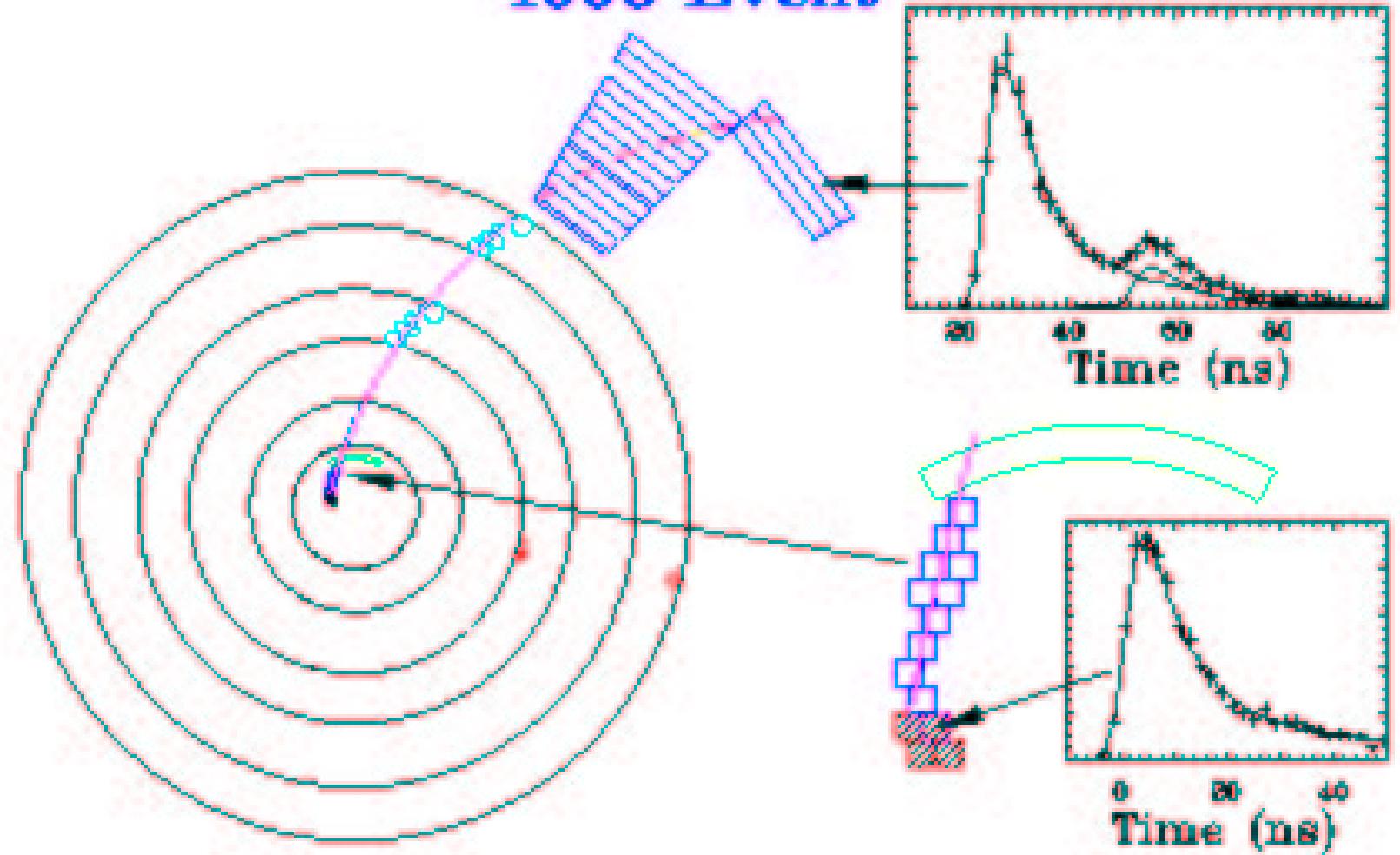
## E949 PNN2 analysis

- E787: PNN2 acceptance approx. half PNN1 acceptance
- Goal is equal PNN2 and PNN1 sensitivity with S/B = 1. This implies  $\times 2$  increase in acceptance and  $\times 5$  increase in background rejection.
- Upgraded photon veto increased PNN1 background rejection. Quantitative assessment of improvement for PNN2 underway.
- Improved algorithms to identify  $K^+ \rightarrow \pi^+\pi^0$  followed by  $\pi^+$  sca trigger in target.

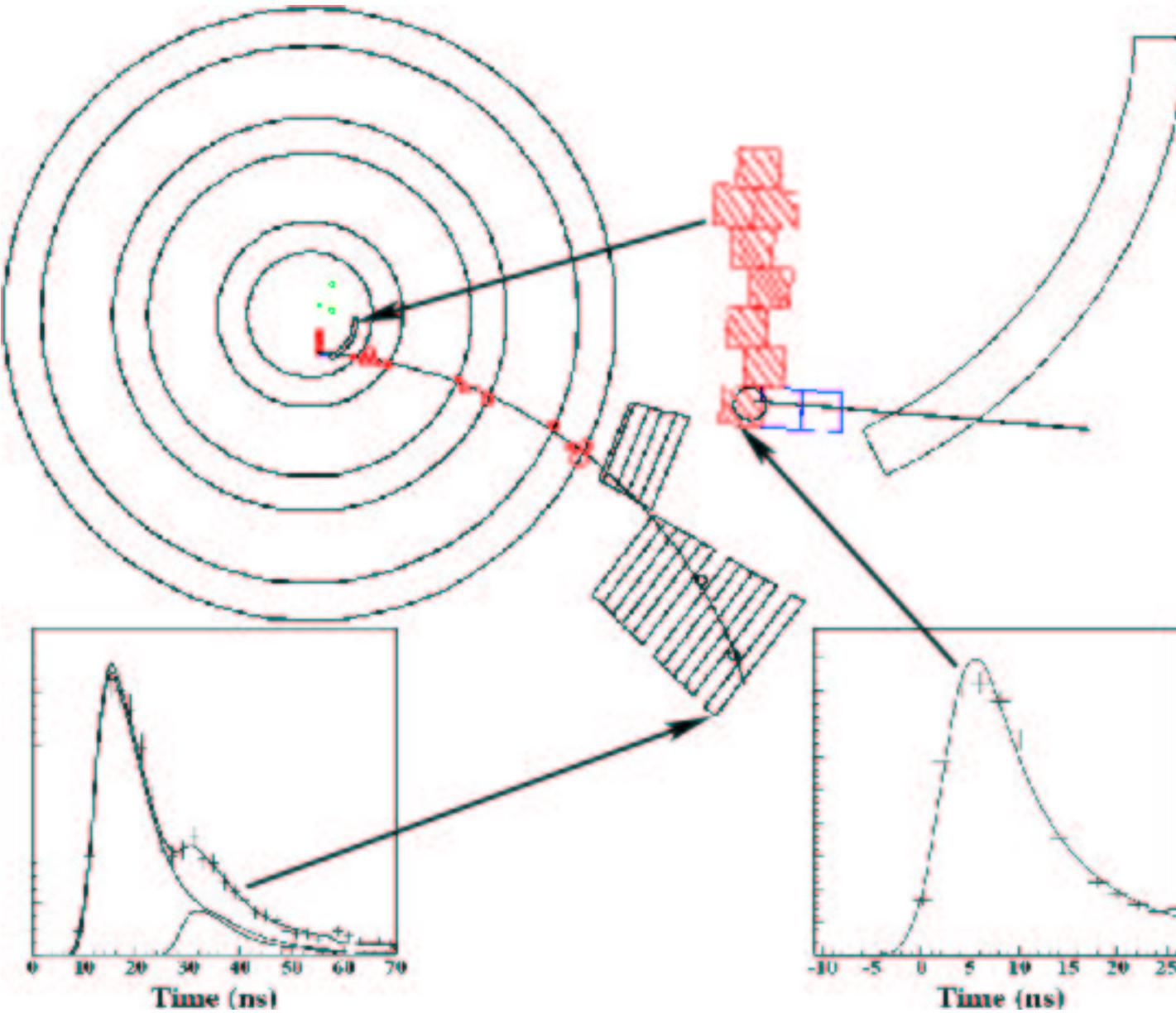


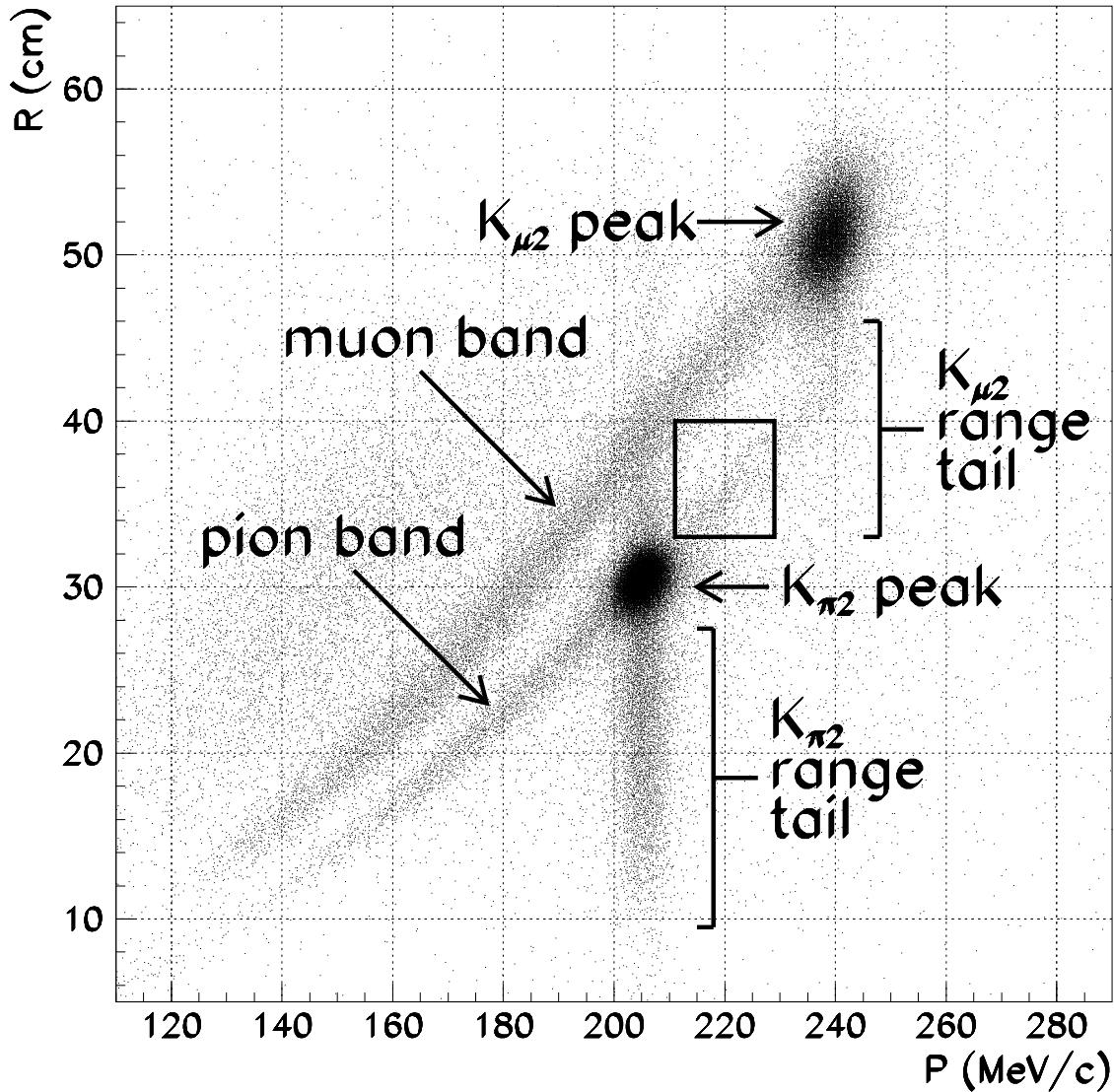
## Candidate E787A

1995 Event



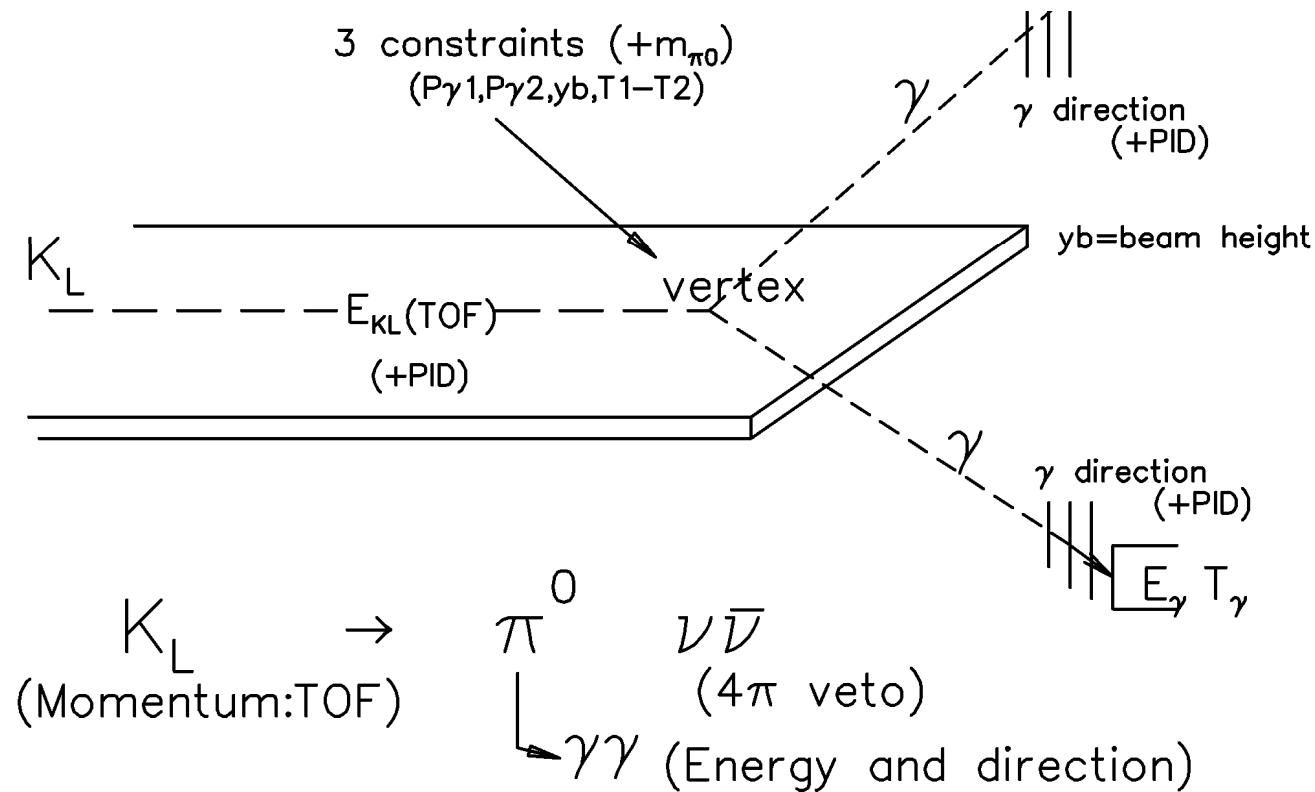
## Candidate E787C

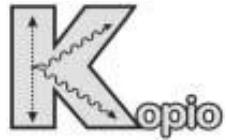




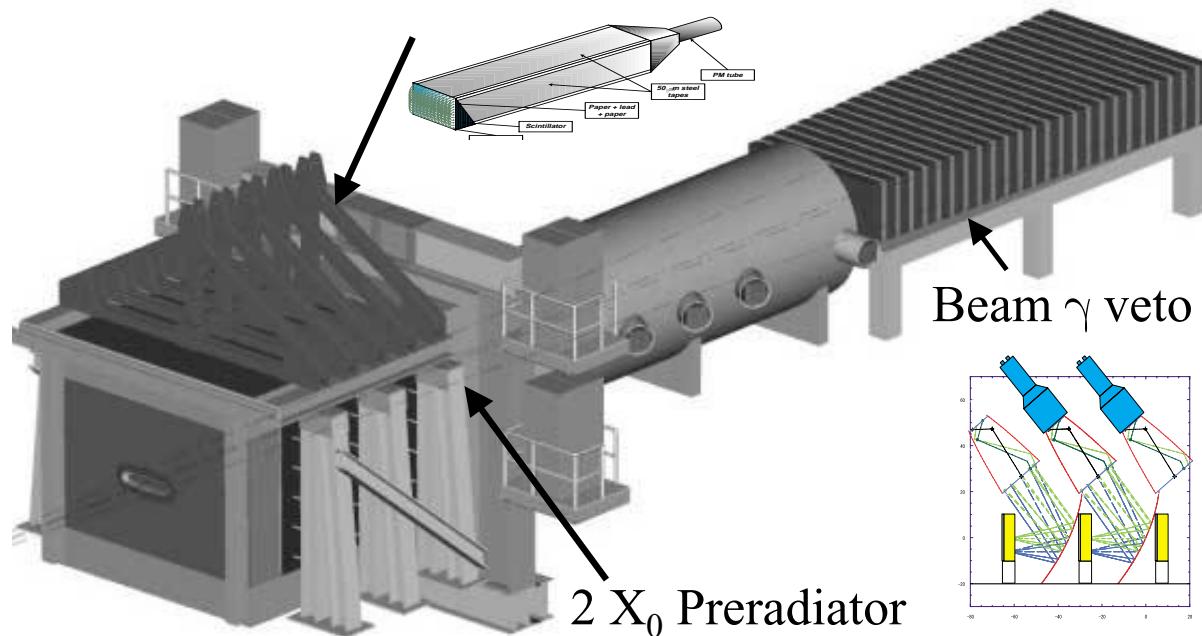
E949 Range *vs* Mo-  
mentum accepted  
by trigger

# KOPIO Beam and Constraints

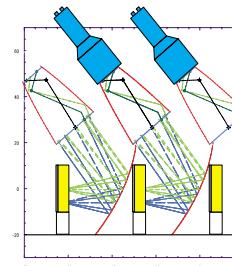




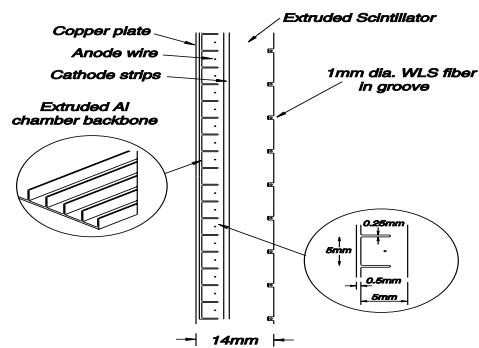
## Shashlyk calorimeter



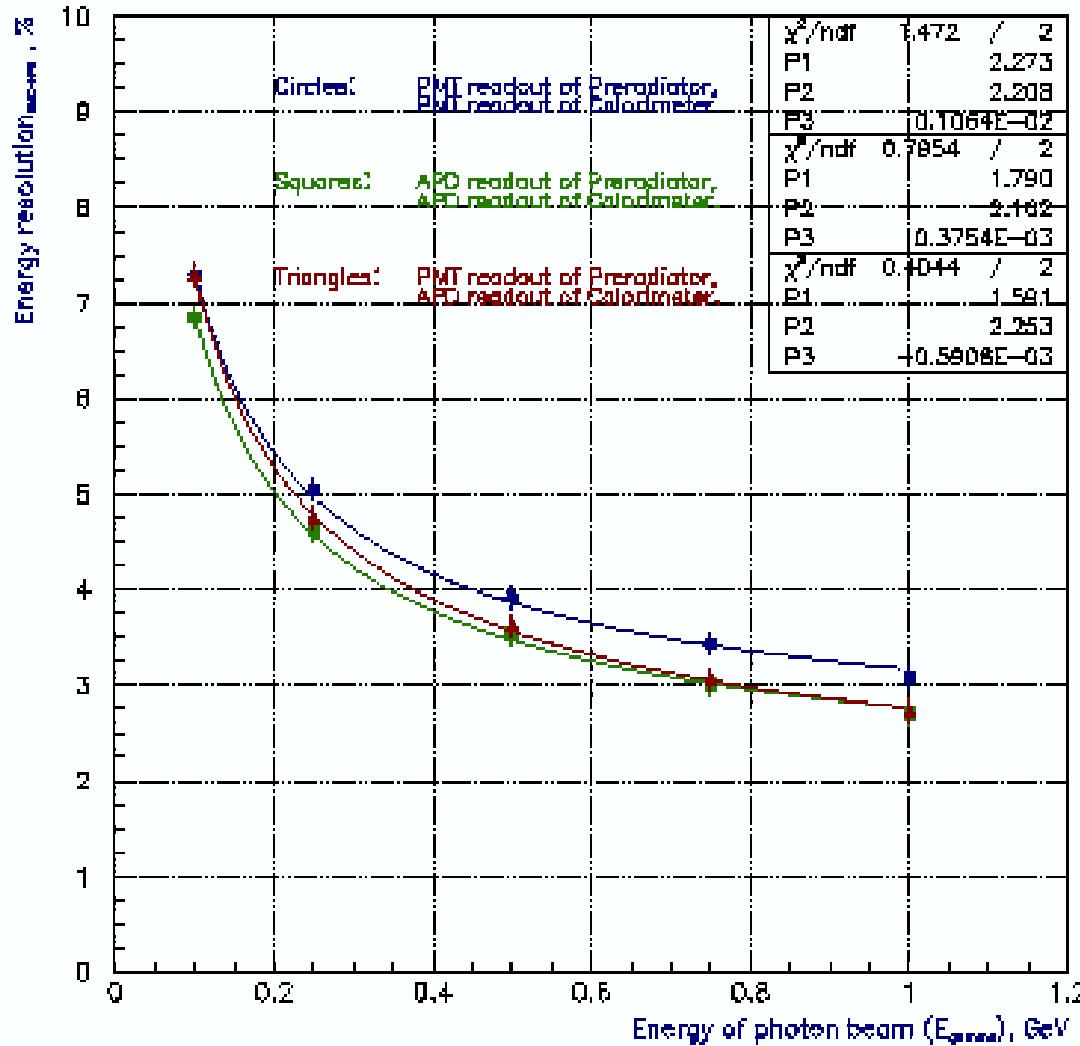
Beam  $\gamma$  veto



Parameter	Minimal Requirement	Expected Performance
$E_\gamma$ resolution	$3.5\%/\sqrt{E}$	$2.7\%/\sqrt{E}$
$\theta_\gamma$ resolution (250MeV)	(25 – 30) mr	23 mr
$t_\gamma$ resolution	$100ps/\sqrt{E}$	$50ps/\sqrt{E}$
$x_\gamma, y_\gamma$ resolution(250MeV)	10mm	< 1mm
$\mu$ -bunch width	300ps	200ps
$\gamma$ -veto inefficiency	$\bar{\epsilon}_{E787}$	$0.3\bar{\epsilon}_{E787}$



# *Simulation:* Combined Energy Resolution



$$\sigma \sim \frac{3\%}{\sqrt{E(\text{GeV})}}$$

## E391a at KEK

